Structural Vibration Suppression Using Fuzzy Logic Control *

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Abstract: This paper designs a fuzzy logic controller to suppress the vibrations of a large space antenna-like ground experimental structure located at the JPL/AF-PL Large Spacecraft Control Laboratory. This fuzzy logic controller provides a simple, yet robust, means to the vibration control of a highly uncertain structural system.

1. Introduction

The vibration control of the large space antenna-like ground experimental structure located at the JPL/AF-PL Large Spacecraft Control Laboratory is an interesting and challenging problem [J]. In the past years, various control approaches, such as, linear robust control, adaptive control, and neural network control have been applied to the vibration control of this structure. In this paper, we will apply fuzzy logic control technology to suppress the vibrations of this structure. In contrast to conventional controllers, which are designed based on well-defined mathematical models, fuzzy logic control (FLC) utilizes linguistic descriptions about the behavior of the system in terms of word statement, These linguistic descriptions are based on the human operator's knowledge about the system, As such, fuzzy logic control provides an effective means to capture the approximate, inexact nature of the real world, and an algorithm which can convert the linguistic control strategy, based on expert knowledge, into an automatic control strategy. As a result, human intelligence can be built into the controller, thus providing autonomous features to the closed-loop system [L], [W].

This paper is organized as follows. Section 2 gives a description of the structure. Section 3 presents the fuzzy logic controller. Section 4 provides some simulation. Section 4 concludes this paper with some remarks.

2. Model Description

This section is based on [J] and [BW]. A schematic diagram of the antenna-like structure is depicted in Figure 1. The main component of the apparatus consists of a

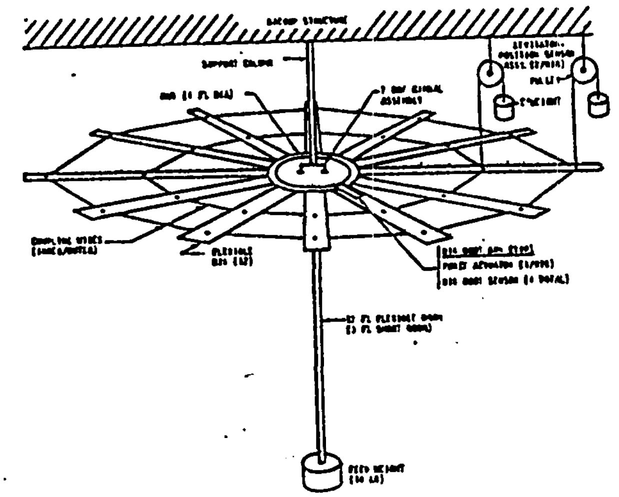

Figure 1: Schematic of the Experiment Structure.

central hub to which 12 ribs are attached. The diameter of the dish structure is 18.5 feet, the large size being necessary to achieve the low modal frequencies desired. The ribs are coupled together by two rings of pretensional wires. Functionally, the wires provide coupling motion in the circumferential direction which cannot be provided by the hub. The ribs are each supported at two locations along their free length by levitators. Each levitator assembly consists of a pulley, a counterweight, and a wire attached to the counterweight which passes over the pulley and attaches to the rib. The hub is mounted to the backup structure through a gimbal platform, so that it is free to rotate about two perpendicular axes in the horizontal plane. A flexible boom is attached to the hub and hangs below it, and a feed mass, simulating the feed horn of an antenna, is attached at the free end of the boom. The boom for our current experiment is 3-feet long.

Actuators

Each rib can be individually excited or controlled by a rib-root actuator. Each rib-root actuator has a solenoid

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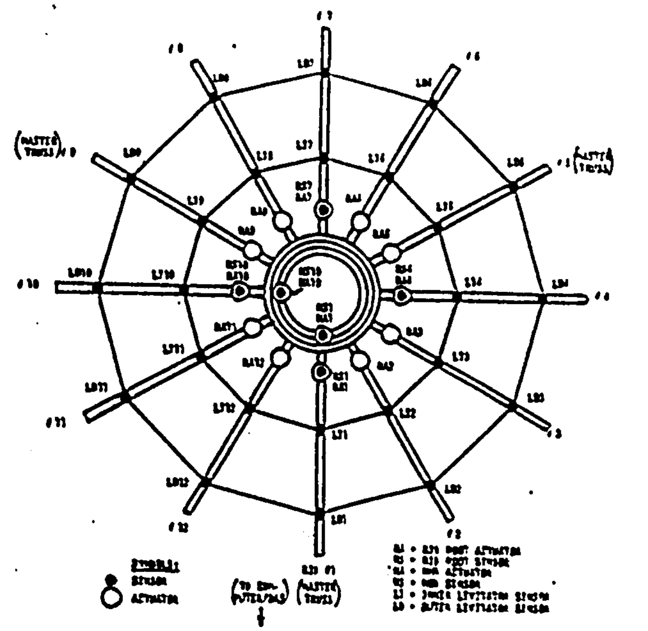

Figure 2: Transducer Location and Labeling - Plan View

design which reacts against a mount that is rigidly attached to the hub. In addition two hub actuators are provided to torque the hub about its two gimbal axes, The hub torques do not provide torque directly, but rather are linear force actuators which provide torque to the hubby pushing at its outer circumference. The torque provided is equal to the force times the lever arm about the axis of rotation, The placement of these actuators guarantees good controllability of all of the flexible modes of motion. The location of the actuators are shown in Figure 2.

sensors

The sensor locations are also shown in Figure 2. First each of the 24 levitators is equipped with an incremental optical encoder which measures the relative angle of the levitator pulley. The levitator sensors thus provide, in an indirect manner, the measurement of the vertical motion of the corresponding ribs at the points where the levitators are attached. There are also four evenly spaced linear variable differential transformers (LVDT) rib-root sensors colocated with four rib-root sensors. The hub angular positions are measured by two rotary variable differential transformers (RVDT) mounted directly at the gimbal bearings. Note that each hub sensor measures the structural response to the actuator mounted orthogonal to itself. Hence, although the actuator/sensor pairs $HA1/HS1$ and $HA10/HS10$ are physically collocated, it is $HA1/HS10$ and $HA10/HA1$ that are collocated in the sense of "dual" variables about a common axis,

Dynamic Model

The system modes can be obtained using finite element analysis. Each rib, and the boom, is divided into 10 beam-type elements and the hub is modeled as a very stiff plate. The normal modes and their frequencies can be obtained by solving a generalized eigenvalue problem in standard form:

$$Kx = \omega^2 Mx$$

where h' is the stiffness matrix, M is the mass matrix, and x is the eigenvector with frequency ω

The symmetry of the structure makes it possible to separate variables and write the circular dependence of a given mode shape by inspection. For a given mode, the displacement of the ith rib is given by ,

$$\text{displacement of } i - th \text{ rib} = \cos(\frac{2\pi ik}{n} + \phi)$$

where n is the number of ribs, and ϕ is a phase angle determined by the coordinate system transformation, Here k is a circular wave number associated with a given mode.

Mode shapes of the structure can be grouped according to their circular wave number k, which ranges from k = 0 to k = 6. Solutions with $k = 0,2,3,4,5$ and 6 are symmetric about the hub, in the sense that all reaction forces on the hub caused by the ribs exactly cancel out. In such modes, which are called "dish modes", neither the hub nor the boom participates in modal motion. On the other hand, modes in which $k = 1$ are asymmetric with respect to reaction forces on the hub. These modes, which are called "boom dish modes", involve motion of the boom, hub and dish structures together. The lower frequency modes are listed in Tables 1 and 2, respectively.

A finite element model consisting of the first 30 flexible modes, 6 actuator inputs, and 30 sensor measurements has been derived in [J), [BW]. The available sensors and actuators are listed in Table 3 and Table 4, respectively. In order to make the design more tractable, here we will base our investigation on a simplified model, which includes the first five modes of table 1, two hub torques (HA1 and HAlO) and two hub angle sensors (HS1 and HS1O). Since the dynamics about the 1-7 axis and the 4-10 axis are decoupled, the problem can be simplified to two single-input, single-output subsystems (HA 1-HS1O and HA1O-HS1).

3. A Fuzzy Logic Controller for Flexible Structure

The mechanism of a fuzzy logic controller is illustrated in Figure 3. It comprises four basic blocks, namely, fuzzifier, fuzzy inference engine, defuzzifier, and fuzzy rule base [L],[W]. The basic function of each component is described below:

- **Fuzzifier:** The fuzzifier maps crisp points in an observed input space U to fuzzy sets in the following fashion,
    1. measures the values of input variables,
    2. performs a scale mapping that transfers the range of values of input variables into corresponding universes of discourse,

Boom-dish modes			
	Frequency, Hz		
Mode No.	Axis 4-10 Subsystem	Axis 1-7 Subsystem	k
1	0.091	0.091	1
2	0.616	0.628	1
3	1.685	1.687	1
4	2.577	2.682	1
5	4.858	4.897	1
6	9.822	9.892	1

Table 1: Normal Boom-Dish Modes

Dish modes		
Mode No.	Frequency (Hz)	k
1	0.210	0
2	0.253”	2
3	0.290”	3
4	0.322’	4
5	0.344*	5
6	0.351	6
7	1.517	0
8	1 .533*	2
9	1.550”	3
10	1.566”	4
11	1.578*	5
12	1.583	6
13	4.656	0
14	4.658*	2
15	4.660’	3
16	4.661*	4
1.7	4.662*	5
18	4.663	6
19	9.474	0
20	9,474*	2
21	9.474*	3
22	9.474”	4
23	9.474*	5
24	9.474	6

* two-fold degenerate modes

‘l’able 2: Normal Dish Modes

Index No.	Actuator
1	RA1 Rib root actuator at rib No. 1
2	RA4 Rib root actuator at rib No. 4
3	RA7 Rib root actuator at rib No. 7
4	RA1O Rib root actuator at rib No.10
5	HAlO Hub actuator about rib 4-10 axis
6	HA1 Hub actuator about rib 1-7 axis

Table 3: Available Actuators

Index No.	Sensor
1-12	Inner levitator rib displacement sensors LI1-LI12
13-24	Outer levitator rib displacement sensors LO1-12
5	HS1 Hub rotation sensor (about rib 1-7 axis)
26	HS1O Hub rotation sensor (about rib 4-10 axis)
27	RS1 Rib root displacement sensor at rib No. 1
28	RS4 Rib root displacement sensor at rib No. 4
29	RS7 Rib root displacement sensor at rib No. 7
30	RS1 O Rib root displacement sensor at rib No. 10

Table 4: Available Sensors

3. performs the function of **fuzzification** that converts input data into suitable linguistic values which may be viewed as labels of fuzzy sets.

Note that a fuzzy set consists of a universe of discourse and a membership function. The membership function can take various forms such as triangular or Gaussian.

- **Fuzzy** Inference Engine: The fuzzy inference engine determines a mapping from the fuzzy sets in the input space U into the fuzzy sets in the output space V using fuzzy approximate reasoning techniques. It has the capability of simulating human decision making based on fuzzy concepts. It can infer fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic.

- **Defuzzifier:** The defuzzier maps the fuzzy sets in the output space into crisp points in the output space in the following way:

  1. a scale mapping, which converts the range of values oft he output variables into corresponding universes of discourse,
  2. defuzzification, which yields a nonfuzzy control action from an inferred fuzzy control action.

  Common defuzzifiers include the max criterion, mean of maximum method (MOM), and center of area (COA) method,

- **Fuzzy** Rule Base: The fuzzy rule base describes how the fuzzy system performs. It consists of a ***dat a base*** and a ***linguistic (fuzzy) control rule base:***

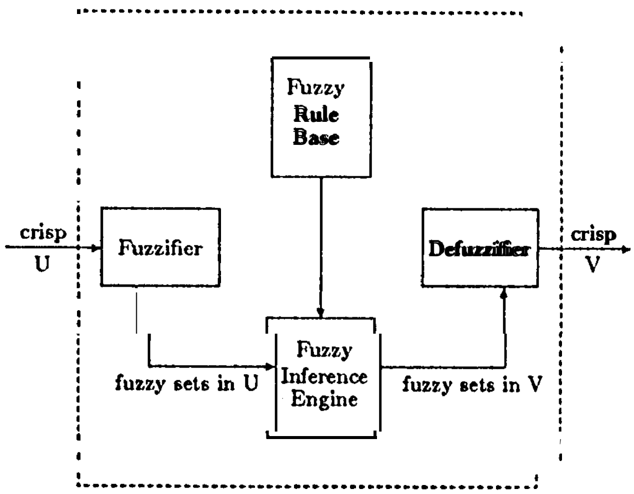

Figure 3: Mechanism of Fuzzy Logic System

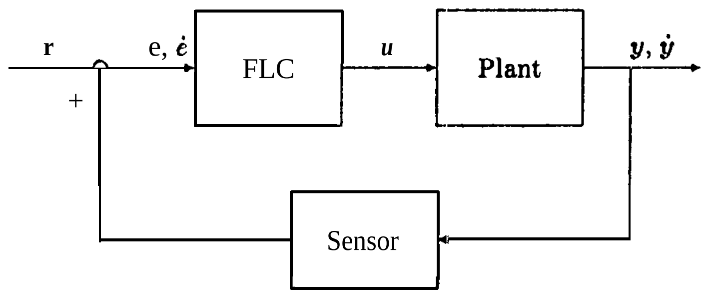

Figure 4: Configuration of Fuzzy Logic Control System

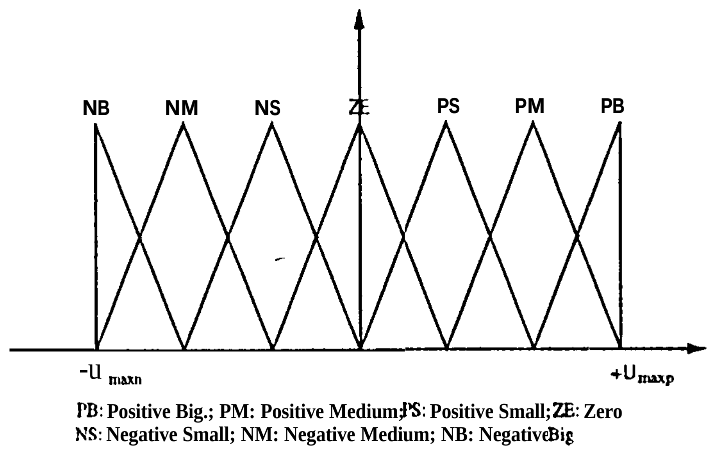

Figure 5: Triangular Membership Function

1. the data base provides necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in FLC,
2. the rule base characterizes the control goals and control policy of the domain experts by means of a set of linguistic control rules.

The fuzzy rule base is often illustrated in the form of a linguistic phase plane [L].

In what follows, we will apply fuzzy logic control techniques to suppress vibrations of the experimental structure. To make the design more tractable, we focus on the simplified model consisting of five boom dish modes, an actuator model HA1 and a sensor HS1O. The developing process of fuzzy logic control systems consists of the following steps.

- Identification of state and control variables
- Definition of performance indices
- Definition of membership functions
- Definition of a rule base
- Tuning the rules and membership functions
- Stability and robustness analysis,
- Real-time implementation

Our fuzzy control system is illustrated in Figure 4, which is similar to a conventional PD controller that takes the error and error derivative as inputs and produces an output to control the plant. The control purpose is to synthesize a linguistic control rule such that the vibrations of the flexible structure due to initial disturbances can be effectively supressed while maintaining the control torque about the two hub gimbal axes within the saturation levels.

'l'he fuzzifier converts the observed real error *signal* and error derivative into several fuzzy subsets within a universe of discourse U, A triangular membership function as shown in Figure 5 is utilized, where U_{maxp} is the largest positive value of the universe of discourse and U_{maxn} is the largest negative value of the universe of discourse. These values can be selected based on the analysis of open-loop response along with a trial and error method and are given as follows

u_{maxp} - $u_{maxn} = 0.3$ for the error

u_{maxp} - u_{maxn} -- 1 for the error derivative

Note that since the error rate is not available, the error derivative is actually derived by defferencing angular position measurements.

The fuzzy inference engine conducts the following tasks:

- Interpretation of connective such as: AN D (rein or multiply) OR (max or add).

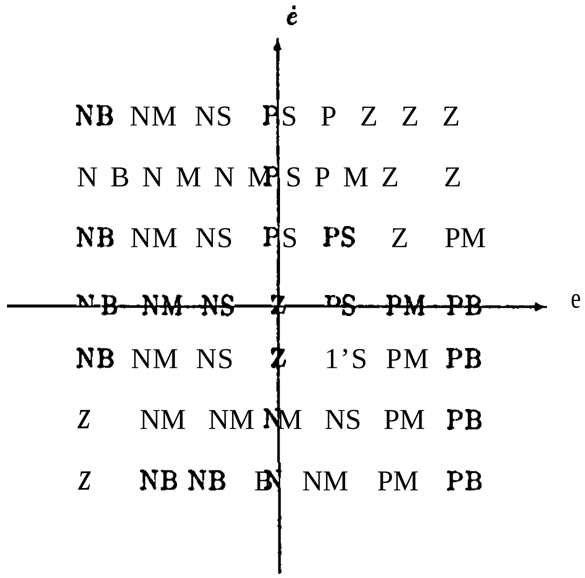

Figure 6: Linguistic Phase Plane

- Selects an inference mechanism such as a compositional rule of inference.
- Selects a **Defuzzification** Method such as the centroid, the (weighted) average of centers of area, and maximum weight.

For the current case, we use *min* and *max* to interpret AND and OR, respectively. The fuzzy rules are determined using the "linguistic phase plane" method **[L].** The resulting linguistic phase plane is shown in Figure 6. Finally, the center of area (COA) method is selected as the defuzzifier.

4. Simulation Results

The performance of the FLC will be evaluated through digital simulation. The setup of the simulation is similar to that given in [BW], that is, the structure is set in motion by a nonzero initial position. Part of the simulation results are given in Figures 7 through 12. Figure 7 compares the open-loop response of the structure with the closed-loop response where the solid line is the open-loop response and the dashed line the closed-loop response. It is seen that the vibration is effectively supreased by the FLC. The system reaches a steady state in about 30 seconds. Figures 8 through 10 show the responses of the control input, error and error derivative. Note that the maximal control torque is well below the torque limit of 2 Nm. To evaluate the robustness of the fuzzy controller to parameter uncertainty, we also simulate the cases where the natural frequency of each mode is perturbed by plus and minus 2070, respectively. The results are shown in Figures 11 and 12. It is evident that the performance is hardly affected by the parameter perturbations.

5. Concluding Remarks

In this paper, we have investigated a fuzzy logic based vibration control scheme. Some remarks are in order,

- The fuzzy logic controller can effectively suppress vibrations caused by a nonzero initial position. It also demonstrates excellent robustness with respect to plant parameter variations. This controller has the conventional PD controller structure, which only utilizes the output measurements,
- Each of the four fuzzy logic controller blocks, namely, fuzzifier, fuzzy rule base, defuzzifier, and fuzzy inference engine influences the performance of the closed-loop system in different ways. For example, selection of membership functions impacts interpolation and inference. Simulation shows that the triangular membership function suppresses the vibration faster than a Gaussian form membership function does.
- Trade-off between the achieved performance and the required control power is an important issue. It is observed that the vibration can be more effectively supressed at the price of larger control power.

6. .Acknowledgement

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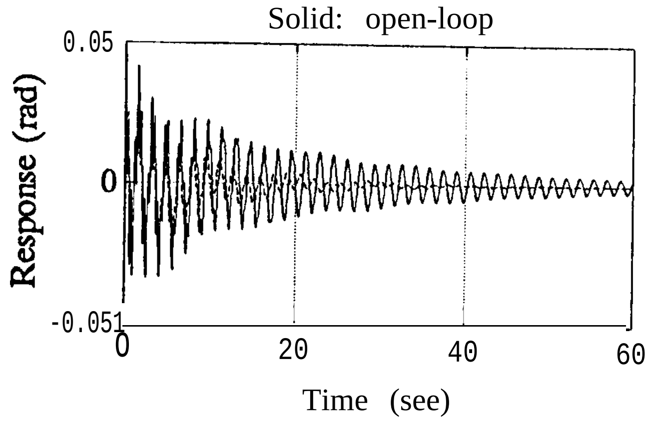

Figure *7:* Open-Loop Response versus Closed-Loop Response (Nominal case)

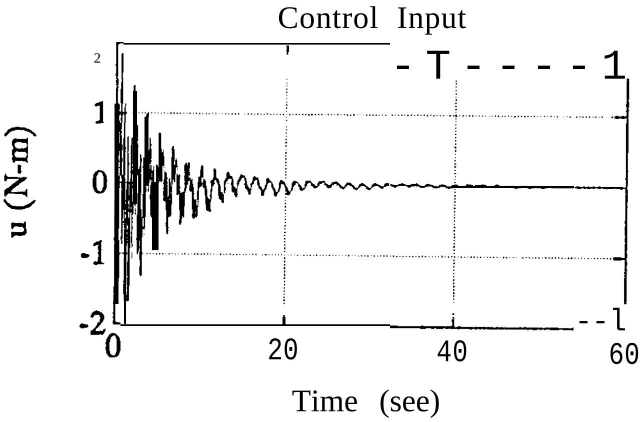

Figure 8: Time Response of The Control Input

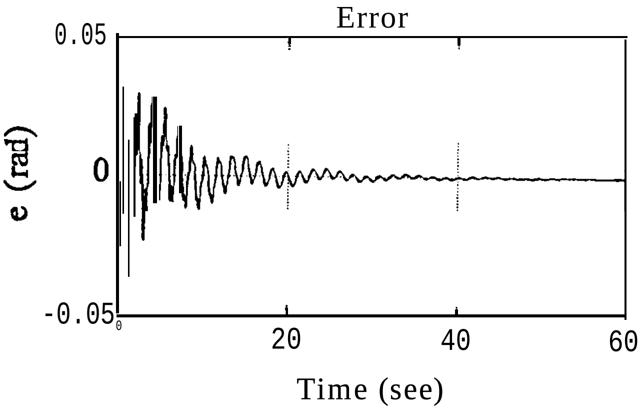

Figure 9: Time Response of The Error

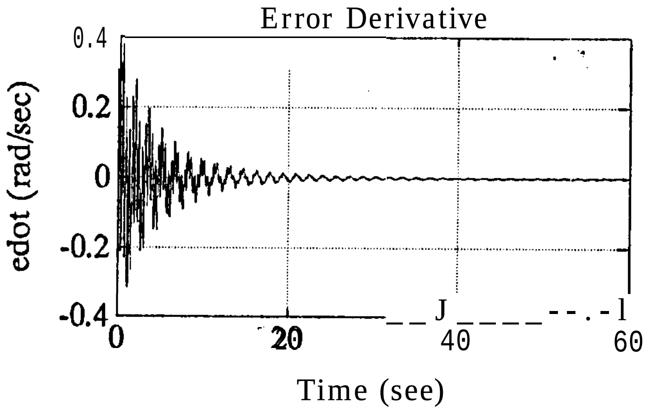

Figure 10: Time Response of The Error Derivative

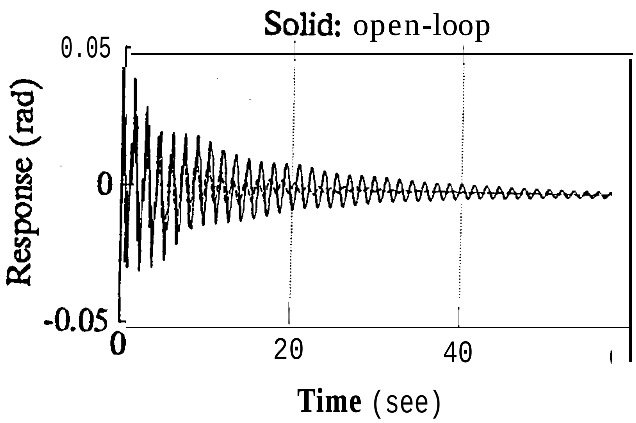

Figure 11: Open-Loop Response versus Closed-Loop Response with plus 20 % variations of the natural frequencies.

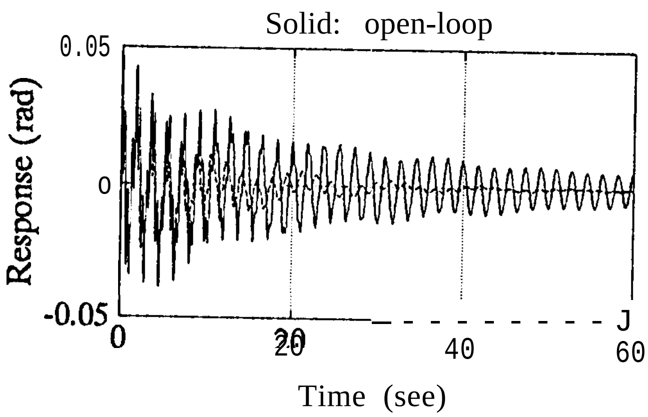

Figure **12: Open-Loop Response** versus Closed-Loop Response with minus 20 % variations of the natural frequencies.