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Control of smart beams using H_∞ to suppress vibrations

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ABSTRACT

This paper deals with the development of a control scheme for the control of vibrations in smart cantilever beams using H-infinity technique. Vibration control plays a very important role in the modern day world especially in control of earthquakes & in aerospace engineering. With reference to this, research is being carried out in this exciting field. Control of vibrations in smart intelligent structures for a SISO case using H∞ method is presented in this paper. Simulation is carried out in Matlab & the results show the effectiveness of the method presented in this paper. This is just a simple exercise to show how powerful the effects of vibrations are died out using the H∞ concept.

Keywords *— Smart structures, H-infinity, Vibration control, Beams, Sensors, Actuators.*

1. INTRODUCTION

A smart material is defined as any material that is capable of being controlled such that its response and properties change under a stimulus. A smart structure or system is capable of reacting to stimuli or the environment in a prescribed manner. Smart Materials and Structures is committed to the understanding, expansion and dissemination of knowledge in this subject matter. To this end, the Journal publishes articles in the following areas [60]:

- Smart materials development and application—including, but not limited to, shape memory alloys and polymers, electro and magnetorheological materials, piezoelectrics, ferroelectrics, piezomagnetics, electro and magnetostrictive materials, thermoelectrics, photovoltaics, electro and magnetocaloric materials, electrochromics, IPMCs, electroactive polymers, energy storage materials, ferroelectrics, self-healing materials and multifunctional materials in general [60].
- Smart materials utilized as sensors and actuators with applications at any scale [59].
- Adaptive structural systems, actively controlled structures with smart materials and other non-traditional actuators [58].
- Sensor and sensor networks for smart materials and structure applications, processing of sensor information for adaptive control or structural health monitoring as well as integration of these sensor networks into materials and structures [57].
- Smart optical materials for modification in spectral shifts and refractive index shift [56].
- Structural health monitoring with applications to ground vehicles, aircraft and civil infrastructure [55].
- Intelligent systems, integrated with sensors, actuators and controllers, applied to automation and robotic systems that utilize smart material systems [54].
- Energy harvesting systems including modelling, applications and implementation issues [53].

Smart materials such as sensors & actuators together integrated or embedded into the structure are what is called a "Smart Structure" and are often called as the intelligent structures, which are used for control of vibrations in structures & earthquakes [52]. Smart materials are a subset of the smart structure [1]. Thus, a smart structure is a distributed parameter system that employs sensors & actuators at different finite element locations on the beam and makes use of sophisticated feedback controllers that analyze the responses obtained from the sensors and use different control logics to command the actuators to apply localized strains to the plant to respond in a desired fashion. Smart structures have also got the capability to respond to the changes in the environment on the plant, whether internal or external such as load changes or temperature changes [2], [61] – [63].

A smart structure system comprises of 4 important sub-parts such as sensors, controller, actuators and the plant (flexible beam), whose condition is to be controlled [53] – [60]. Each component of this smart structure system has a certain functionality and the entire sub-systems are integrated to perform a self-controlled smart action, similar to a living creature who can "think", make judgment and take actions on own at the appropriate time, thus inducing the smart & intelligentness [3] – [10].

The paper is organized as follows. A brief review about the smart structures is presented in the introductory section. The POF control law used in the research work is presented in section 2 followed by the control simulations in section 3. Justifications of the simulation results are presented in section 4. The section 5 presents the conclusions of the work done. This is followed by the references & the author biographies.

2. CONTROLLER DESIGN USING H-∞

H_∞ is a robust control problem which is used now-a-days for robust-stability controlling the dynamically varying LTI-systems. To understand concept of H infinity control, let us consider the smart beam model represented by standard SS model [1] – [10].

$$\dot{x} = Ax + Bu \quad \&$$
$$y = Cx + Du$$

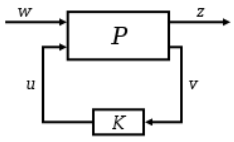

Fig. 1: Block diagram of a H-infinity controller

Further, let this plant be a nominal-plant (strictly) & R is scalor value function (radius within the R H_∞. The next step is to define a family of plants which are in the neighborhood of P & consisting of all proper real rational matrixes (P+ΔP) having the same no. (in terms of Mc-Millan degree) of poles in Re(s)>0 as has the plant P, the perturbation ΔP is going to satisfy the inequality bound criterion given by

$\| \Delta P (j\omega) \| < \| (j\omega) \|$ for all $0 \leq \omega \leq \infty$ [11] – [20].

For a real rational value of the gain K, the RSC (robust-stab-criteria) is that K balances (stabiliszes) out all plants in P. Stability strength implies inner good stability, that the four matrixes should be belonging to the control H-infinity. If the above mentioned norm is satisfied, then the small gain is guaranteed by the robust stability condition in the control algorithm. The H_∞ control problem is stated as follows. Let us assume that we are having a system given by Σ. Let the system be a LTI (either in CT or in DT domain) with 2 inputs w, u & 2 outputs z and y. The w input is exogenous input (the system which is acted upon by a disturbance). z is the o/p of system & depends on the exogenous input w, which we want to minimize [21] – [30].

Now, the o/p of system, i.e., *y* is a measurement, which we make on the LTI system. Use y to choose the input of the system, i.e., u, which in turn is the tool we have to minimize the effect of w on z. In this process, use a constraint that has to be imposed on the mapping from y to u. This should be such that the CLCS is stable. This is a good thing since we do not want the states of the modelled system to become too large, when we are trying to regulate the performance of the system. The effect of w on z after closing the feedback loop in the system is measured in terms of the energy concept and the worst disturbance parameter, i.e., w [31] – [40].

Our measure, which will be equal to the closed-loop H_∞ norm of the system is defined as the supremum over all the disturbances $\neq 0$ due to the energy quotient which is flowing out of the plant system & the energy flowing into the system. Loop shaping is also done in this type of control, which will guarantee complete stability as we determine the H infinity norm, i.e., the 3rd norm in the robust stability analysis. The H_∞ control theory involves suppressing of the sensitivity matrix TF. This suppression takes place at lower frequencies for performance with high gain. At the same time, the transmissivity at high frequency is suppressed, i.e. loop shaping in the control arena of the plant model. A cost penalty is also associated with the control actuator limitation in order to achieve a limited performance design [41] – [50].

H-infinity, control theory was implemented with the Matlab Robust Controls Toolbox & was shown to be a beautiful, compact, direct method. This method was used to change the MIMO system's frequency response in order to achieve both robustness and system performance. A scientific model for the considered intelligent beam was planned / developed and utilized for the vibration control purposes in our examination work. First, the beam model is obtained using fundamental principles, then the state space model, The beam is excited by an exciter & is then subjected to vibrations. These vibrations are sensed by the sensor. Vibrations are sensed by the sensor and in turn given as input to the H_∞ controller [51] – [53].

Loop shaping is done w.r.t. the robust stability point of view, at the same time, optimization process is also carried out using the optimization commands available in Matlab. The controller in turn gives the signal to the actuator, which in turn gives anti-signals to make the vibrations die down which are caused by disturbance signals, thus the overall vibrations of the system is reduced using the destructive interference criteria. While the controller is designed, only first few vibratory modes are used (2) as these are the dominant ones. Output responses are seen with & w/o the H-infinity controller in order to show the effect of the control phenomenon [51] – [60].

Lot of researchers have worked on the H-∞ control, some of the concepts are being used in our work for the vibration suppression of beams [51] – [60].

Robust stability is also obtained as the poles are far away from the imaginary axes in the CT system, while it is inside the unit circle in the discretized model of the plant. Another control law called H-infinity robust control for regular variations of the frequency that incorporates the uncertainty bounds on the natural frequency (bode plot) was developed which was implemented on a smart cantilever beam, which showed excellent results when the open loop response & the closed loop responses are compared both qualitatively & quantitatively compared to all other types of control strategies developed. The simulation results are shown in the Figs. 3 & 4 respectively [51] – [60].

3. MATHEMATICAL MODEL

The mathematical model is derived from the first principles for the plant (smart cantilever beam), i.e., for a single input single output state space model (state equation and the output equation) of the smart structure developed starting from the fundamentals of the state space theory and is given by [51] - [60]

$$\dot{\mathbf{x}} = \mathbf{A}\,x(t) + \mathbf{B}\,u(t) + \mathbf{E}\,r(t),$$

$$y(t) = \mathbf{C}^T\,\mathbf{x}(t) + \mathbf{D}\,u(t),$$

with

$$\mathbf{A} = \begin{bmatrix} 0 & I \\ -\mathbf{M}^{*-1}\mathbf{K}^* & -\mathbf{M}^{*-1}\mathbf{C}^* \end{bmatrix}_{(4\times4)},$$

$$\mathbf{E} = \begin{bmatrix} 0 \\ \mathbf{M}^{*-1}\mathbf{T}^T\mathbf{f} \end{bmatrix}_{(4\times1)}$$

$$\mathrm{B} = \begin{bmatrix} 0 \\ \mathbf{M}^{*-1}\mathbf{T}^T\mathbf{h} \end{bmatrix}_{(4\times1)},$$

$$\mathbf{C}^T = \begin{bmatrix} 0 & \mathbf{p}^T \end{bmatrix}_{(1\times4)},$$

$$\mathbf{D} = \text{Null Matrix},$$

where the parameters $r(t)$, $u(t)$, **A, B, C, D, E,** $\mathbf{x}(t)$, $y(t)$ represents the external force input, the control input, system matrix, input matrix, output matrix, transmission matrix, external load matrix, state vector and the system output (sensor output) [49]. This model is used for developing the controller in simulink environment [48] [21] – [30] and to observe the effectiveness of the controller.

4. SIMULATION RESULTS

5.

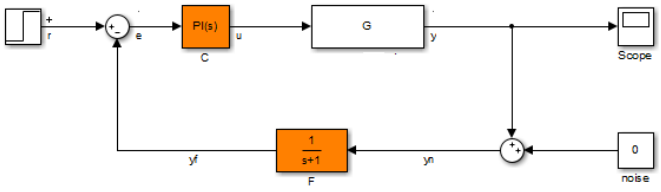

Fig. 2 : Simulink model for the H-∞ controller design

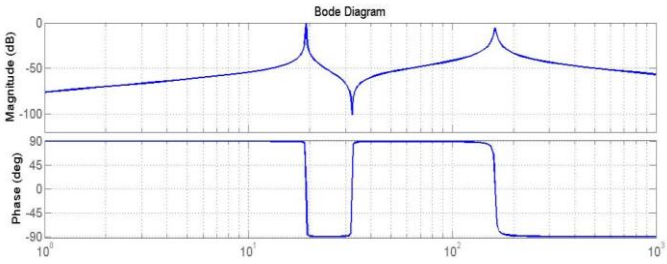

Fig. 3: Frequency response plot showing the 2 vibratory modes ω_1&ω_2

Table 1: Quantitative results of smart beam with H-infinity control

No.	OL Response	CL response
Magnitude	1.5 V	1.5 V
Settling time	10 s	0.4 s

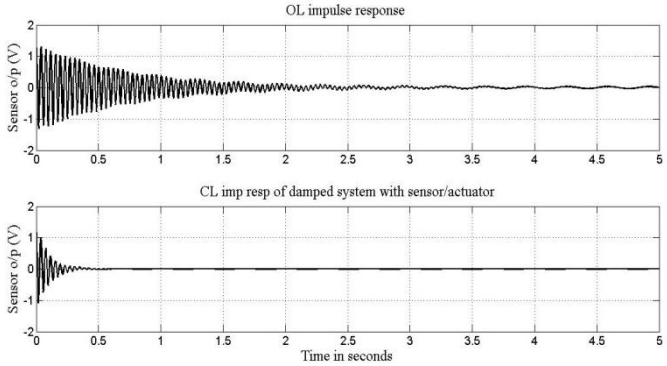

Fig. 4 : OL & CL responses of smart beam with H-∞control

6. CONCLUSIONS

In this paper, control of vibrations in smart intelligent structures for a SISO case using H-infinity method was presented. The simulation results show the effectiveness of the method developed for vibration suppression. The beam was divided into a number of finite elements & the best location for the placement of the piezo sensor actuator pair was found out through simulations done in Matlab. Only 2 modes are considered in the design as these 2 modes are the most predominant ones. The H-infinity model is developed in the Matlab-Simulink environment & after designing the contro0ller, the model is run for a certain amount of period & the results are observed on the scope connected to the plant in the model with and without the H-infinity controller. From the simulation results, it is observed that without controller, the transient responses are predominant, while with the incorporation of the controller in the loop with the plant, the transient responses dies away quickly & the output settles at a faster rate.

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BIOGRAPHIES

Dr. T.C. Manjunath was born in Bangalore, Karnataka, India on Feb. 6, 1967 & received the B.E. Degree (Bachelor of Engg.) from R.V. College of Engg. (Bangalore Univ., B'lore) in the year 1989, M.E. degree in Automation, Control & Robotics from the prestigious Govt.'s LD College of Engg., (Gujarat Univ., Ahmadabad) in the year 1992 and Ph.D. in Systems & Control Engineering from the prestigious Indian Institute of Technology Bombay (IIT Bombay) in the year 2007 respectively. He has got a teaching (academic), research & administrative experience of more than 25^{+} years in various engineering colleges all over the country (Karnataka, Gujarat, Maharashtra). He has worked in the levels of Lecturer-Asst. Prof., PG Coordinator, Prof-i/c HOD-Prof. & Head, Director-Research, i/c Principal & as Full time Principal (> 6 yrs-Atria IT, BTLITM, HKBKCE, Dr. AIT) in the various institutions where he has worked so far. Currently, he is working as the Principal of the famous NICE group's 'Nandi Institute of Technology & Management Sciences' in Bengaluru, Karnataka. He has also worked as a Project Assistant and as a Research Engineer in the Systems and Control Engineering (IIT Bombay, India) and worked on control of space launch vehicles using FOS feedback technique in IITB. He has published a number of papers in various National, International journals and Conferences in India & abroad and published a number of textbooks, notable among them being ('*Introduction to robotics*' - 1st edition, '*Fast Track to Robotics*' - 4th edition, '*Fundamentals of Robotics*' in 2 volumes, Vol-1 and Vol-2 along with a CD which contains about 200 C / C++ programs for performing various simulations on robotics – 5th edition, '*Examination Security System - Design & Development of Examination Mechanism Using Electronic Box'* from Germany costing around 49 Euros). He has also published a number of '*book chapters'* in various edited books from renowned publishers. He has also published a research monograph in the International level from the Springer-Verlag publishers (Europe) based on his Ph.D. thesis topic titled, "*Modeling, Control and Implementation of Smart Structures*", Vol. 350, LNCIS, costing 114.95 Euros. He is a member of 21 professional societies. Some of them are … He is a member of IEEE for the past 13 years (currently Sr. Member), Sr. member of IIIE, SPIE student member and IOP student member for 4 years, life member of ISSS (India), life member of additive manufacturing society of India (LMAMSI), life member of the ISTE (India), life member of ISOI (India), life member of SSI (India), life member of the CSI (India), Life member of IMAPS, Sr. Member of IACST (Singapore) and life member cum fellow of the IETE (India), AMSI, Chartered Engineer from IE (I) and Fellow of the Institute of Engineers (FIE). He has given a number of guest lectures / expert talks and seminars in many institutions across the country and participated in more than 2 dozen CEP / DEP courses, seminars, workshops, symposiums, besides conducting a few courses in the institutions where he worked. He was awarded with the "Best research scholar award in engineering discipline" for the academic year 2006-07 for the entire institute from the Research Scholars Forum (RSF) from Indian Institute of Technology Bombay (IITB). This award was presented in recognition of the significant contribution to the research (amongst all the researchers in all disciplines) in IIT Bombay. Also, he was conferred with the best paper awards in a number of conferences. He was also conferred with the prestigious Rajiv Gandhi Education Excellence Award, RashtriyaVidyaGaurav Gold Medal Award & International educational excellence award (in recognition of sterling merit excellence performance and outstanding contribution for the progress of the nation & world-wide) from New Delhi in the year 2013 w.r.t. his achievements in the field of education, academics, administration & research. He was also instrumental in getting Research centres (12 nos.) along with M.Tech. programmes& new UG programmes in the colleges where he has worked so far as the administrative head. He was also responsible for getting AICTE grants under MODROB scheme for the development of the Robotics & Mechatronics Labs in one of the colleges where he worked. Apart from which, he has brought a number of grant-in-aid for the conduction of various events like workshops, conferences, seminars, projects, events, etc., wherever he has worked [from VTU, DST, IETE, CSI, IEEE, IE(I), VGST, KSCST, Vodafone, Uninor, etc.] from different sources. He has visited Singapore, Russia, United States of America, Malaysia and Australia for the presentation of his research papers in various international conferences abroad. His biography was published in 23rd edition of Marquis's Who's Who in the World in the 2006 issue. He has also guided more than 2 dozen projects (B.E. / B.Tech. / M.E. / M.Tech.) in various engineering colleges where he has worked, apart from guiding a couple of research scholars who are doing Ph.D. in various universities under his guidance. Many of his guided projects, interviews, the events what he had conducted have appeared in various state & national level newspapers and magazines (more than 110 times). He has also reviewed many research papers for

the various national & international journals & conferences in India & abroad (more than 5 dozen times). He has also organized a number of state& national level sports tournaments like yogasana, chess, cricket, volleyball, etc. He is also an editorial board / advisory board / reviewer member and is on the panel of many of the national & international Journals. He has also served on the advisory / steering / organizing committee member of a number of national & international conferences. He has given many keynote / invited talks / plenary lecturers in various national & international conferences and chaired many sessions, was the judge, special invitee, guest of honor& was the chief guest on various occasions. He has also conducted / organized / convened / coordinated more than 175^{+} courses / workshops / STTP's / FDP's / Technical paper fests, Student level competitions & Symposiums, etc., in various engineering colleges where he worked so far. He has also taken many administrative initiatives in the college where he has worked as HOD, Principal & also where he is currently working as Principal, besides conducting all the semester university exams successfully as chief superintendent, deputy chief superintendent, squad member, etc. Some of the special administrative achievements as HOD, Principal & Head of the Institution are …. He improved the results of the various branches in East West Inst. of Tech. / New Horizon College of Engg. / Atria Inst. of Tech. / BTL Inst. of Tech. / HKBK College of Engg. / Dr.Ambedkar Inst. of Tech. He gave more importance to the development of in-house projects for the final years. He has also He motivated many of the faculties to take up take up consultancy works & did it efficiently, so that the college got some good income. He made the faculties to take up research (Ph.D) work or do M.Tech. by compelling them constantly to purse for higher studies. As an administrative head, he made the faculties to publish paper in either national / international journals & conferences at least one in an academic year. He started the student chapters in all the branches such as IETE, IEEE, ISTE, CSI, SAE, ISSS, ISOI& also conducted a number of events under their banners. He brought in power decentralization in the institute by developing the habit of making coordinator-ships for various works, getting the work done by monitoring and following it up successively. He was also involved in TEQIP-2 process in Dr. AIT along with the development of many of the autonomy works. He conducted a number of exams from public sectors & private sectors such as GATE exams, CET / COMED-K, KPSC, Police Exams, Inst. of Civil Engineer exams & conducted a number of state & national level examinations like Defense, PG entrance exams, Medical, KPTL in the college so that the college could get some revenue (under the banner of revenue generation scheme). He started the weekly monitoring of the staff & students. He developed the counseling of student data booklets & that of the faculty work-books. All the laboratory manuals were developed in-house, printed & given to the students (both in the hard as well as in the soft copy). He used to conduct the academic & governing council meetings regularly along with the HOD's meetings time to time. He had looked after the NBA process in Fr. CRCE, BTLITM, HKBKCE& in Dr. AIT. He conducted the prestigious 7^{th} IETE ICONRFW & the 28^{th} Karnataka State CSI Student Convention. He introduced the scheme of best lecturer award / best HOD award / best non-teaching award / service awards concept / Principal cup / Departmental cup, etc. in the colleges where he worked as administrative head. He created a record placement of more than 600 students in Atria Inst. of Tech. / BTLITM & in HKBKCE with the help of the placement department. He helped the management to fill up many of the student admissions in the first year of UG (B.E.) & in PG (M.Tech.) course. He created a number of hobby-clubs, EDC cells, Innovation & Incubation centres, centre of excellences in the institute for the staffs & students to work towards development of prototypes, models, and projects. He started the faculty seminar series in the institute so that every faculty gives a lecture of 45 mins with 15 mins discussion at least once in a month. He introduced the concept of coaching class / tutorial classes for the weak students & remedial class concept for the failed students, which yielded successful results apart from the training of top 10 students for getting ranks (9^{th} / 3^{rd} Rank). He made the students to get university ranks in BTL & HKBKCE in UG stream. He started certificate oriented courses of 3 months & 6 months for the various types of people, especially on Saturdays & Sundays. He made the students to participate in competitions outside the college & win a number of prizes, brought laurels to the institution. He helped the students to get some financial assistance using sponsors for the cultural events. He brought a grant of nearly Rs. 3 crore till date in the various organizations where he has worked so far with help of faculties. He developed the Innovation & Entrepreneurship Development Cell in HKBKCE & did a number of programs under its belt. He was responsible for some of the UG students of HKBKCE to make them establish a start-up company in the college itself by name '*pentaP systems*'. He made more than one dozen MOU's with reputed firms & sectors with the college and utilized all the advantages of the signed MOUs with the companies. He streamlined many of the process in the office level & that of the departmental level by developing new formats for the smooth conduction of various processes along with excellent documentation. He developed the culture of making up of small / mini hobby projects by the students. He developed the system documentation of the entire departments & that of the college. Under industry-institute interaction, he conducted a number of industry oriented courses like CADD course, ANSYS course, Oracle course, Infosys campus connect courses (18 batches rolled out in HKBKCE), Software testing, etc. His special areas of interest are Control systems, DSP, AI, IP, Robotics, Signals & systems, Smart Intelligent Structures, Vibration control, Instrumentation, Circuits & Networks, Matlab, etc.……

Mr. Arun Kumar G (B.E., M.E., (Ph.D.), MISTE, IETE, IAENG) was born in Davanagere, Karnataka, India on Oct. 15th, 1981 & received the B.E. Degree (Bachelor of Engg.) from STJ Institute of Technology, Ranebennur in Karnataka in the year 2004, M.Tech. degree in Digital Communication & Networking from the prestigious UBDT College of Engg., Davanagere in the year 2008 and Pursuing Ph.D. in Electronics in Visvesvaraya Technological University, Belgaum as a research scholar in VTU in the department of ECE. He has got a teaching & administrative experience of more than 8 years in engineering colleges in Karnataka. He has written a number of notes in various subjects as Basic Electronics, AEC, Power Electronics, Communications & his notes are widely famous all over the country. He has attended a number of certificate courses, workshops, FDPs, Symposiums, etc. He has published more than 2 dozen papers in various subjects of engineering field. His current areas of interest are control systems, power electronics, basic electronics, micro-controllers, embedded systems, communications etc….