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Development of Discrete Output Feedback Sliding Mode Control for Controlling the Vibrations

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Abstract—

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. In this paper, we develop the controller for controlling the vibrations of beams using discrete output feedback based sliding mode control is presented. Simulation are carried out in Matlab & the results show the effectiveness of the method presented in this paper. When the designed controller is put in the loop with the plant, the plant performs well and the vibrations are damped out in a quicker time. The performance of the designed controller is thus evaluated for vibration control and the conclusions are drawn.

Keywords—Smart structures, Discrete output feedback sliding mode control, Vibration control, Beams, Sensors, Actuators.

I. INTRODUCTION

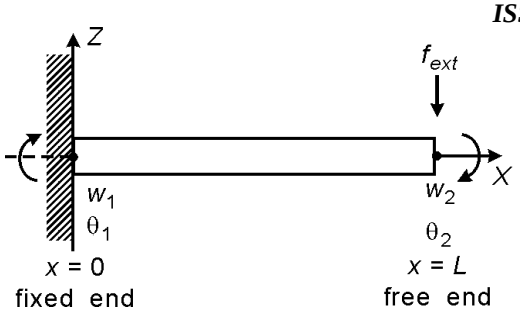
Smart materials such as sensors & actuators together integrated or embedded into the structure are what is called a "Smart Structure" and are often called as the intelligent structures, which are used for control of vibrations in structures & earthquakes. Smart materials are a subset of the smart structure [1] [9]. 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 [1] – [10].

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]. 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]. Smart materials and smart structures, often called as the intelligent structures form a new rapidly growing interdisciplinary technology in the modern day world, especially after the world trade centre disaster [4]. This smart structure technology enhances the structural properties by integrating sensors, actuators, signal-processing, electronics and control technologies into it, thus resulting in an improved overall dynamic performance [5]. These intelligent structures form the basis for the nanotechnology concepts.

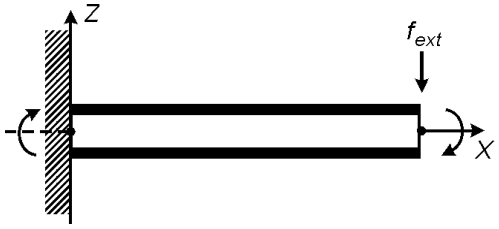
Numerous applications of this technology can be found in aerospace, civil, transportation, defense, flexible manipulators, MEMS, NEMS, bio-technology, automobiles, communications, antennas and in earthquakes [55] - [60]. One exciting and interesting example of its applications is the active vibration control (AVC) in structures such as in beams, plates, structures and in shells, which is our topic of research [11] – [20]. The paper is organized as follows. A brief review about the smart structures is presented in the introductory section. The 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.

II. DESIGN OF SLIDING MODE CONTROLLER

In this section, a brief review about the type of control strategy used to curb the vibrations of a smart cantilever beam along with the simulation results & justifications is presented in this context [21] – [30] w.r.t. the discrete time sliding mode control point of view. It is a well-known fact that SMC is a robust algorithm for linear & non-linear control systems. Various applications in the world has made use of the CT SMC till date. But, there are lot of dis-advantages of the CT SMC techniques. DT SMC also can be used for lot of applications, but even then this control strategy has got lot of dis-advantages. Very less information is known w.r.t. discrete output feedback sliding mode controllers & not that much of work has been done w.r.t. discrete output feedback sliding more controllers. We regularly expect that the f_s is high to accept that the CLCS is CT. There is another method of designing the SMC in DT & that is using the DT model of the system which is sampled & which is under control [31] – [40]. The plant is shown in the Fig. 1, i.e., a regular flexible beam and a smart aluminum cantilever beam bonded with surface mounted piezoelectrics.



(a) A regular flexible beam



(b) A aluminum Timoshenko cantilever beam bonded with surface mounted piezoelectrics

Fig. 1 : A regular flexible beam and a smart aluminum Timoshenko cantilever beam bonded with surface mounted piezoelectrics

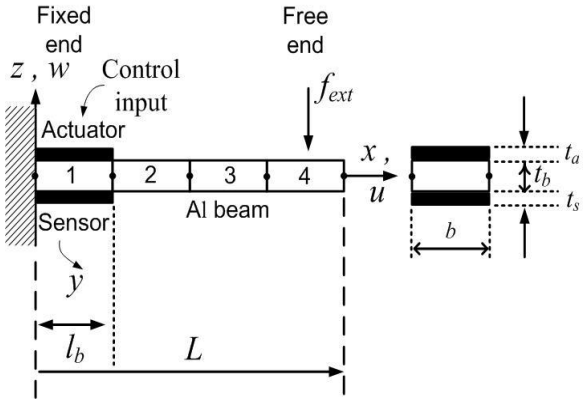


Fig. 2 : Model 1 (PZT placed at FE position 1, fixed end)

The single input single output state space model (state equation and the output equation) of the smart structure developed for the system shown in Fig. 1 is given by

$$\dot{\mathbf{x}} = \mathbf{A}\,x(t) + \mathbf{B}u(t) + \mathbf{E}r(t),\; y(t) = \mathbf{C}^T\mathbf{x}(t) + \mathbf{D}u(t),$$

with

$$\mathbf{A} = \begin{bmatrix} 0 & I \\ -\mathbf{M}^{*-1}\mathbf{K}^* & -\mathbf{M}^{*-1}\mathbf{C}^* \end{bmatrix}_{(4\times4)},\; \mathbf{E} = \begin{bmatrix} 0 \\ \mathbf{M}^{*-1}\mathbf{T}^T\mathbf{f} \end{bmatrix}_{(4\times1)}$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ \mathbf{M}^{*-1}\mathbf{T}^T\mathbf{h} \end{bmatrix}_{(4\times1)},\quad \mathbf{C}^T = \begin{bmatrix} 0 & \mathbf{p}^T \end{bmatrix}_{(1\times4)},\quad \mathbf{D} = \text{Null Matrix},$$

where the parameters $r(t)$, $\mathbf{u}(t)$, **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). This model is used for developing the controller.

State f/b based, DT output feedback SMC has received quite some attention over the years in the beginning of the 21st century. There are certain problems associated with it compared to CT sliding mode, which is the limited switching speed, but when tuned properly, it yields very good results. The f_s in CT is thought to be ∞, in DT, it is constrained by the f_s. In DT, the exact sliding strategy cannot be attained. On the other hand, one of the best achievable result to get into discrete mode is to control the CLCS inside of a little limited area around the exchanging surface called as the semi-quasi sliding mode band. As compared to the DT state-based SMC, DT output-based SMC has received little attention & not much work is done in this regard & this is one of the area which we are exploring to curb down the vibrations of the smart beam. Here, in this approach, we have focused on the transfer function (TF) approach [41] – [50].

We have focused our attention w.r.t. design of an o/p-based DTSM controller using the state-space representation of the continuous time cantilever beam plant in the linear mode. Using this new approach, the outline of the o/p based controller can be connected effortlessly to MIMO plants also as well. Enhancements can be made by the utilization of disturbing function estimation & utilizing the state observation concept in the reducer order mode. Modelling of the beam was done first, then the beam is subjected to vibrations, the vibrations are sensed by the sensor, which in turn is given as input to the discrete o/p f/b based SMC, then o/p of the controller is given as i/p to actuator, which in turn gives anti-signal to the sensor output, superimposes with the sensor signal & thus nullifies the vibrations. The main task in planning the o/p f/b controller is to select the sampling interval τ [51] – [60].

The max. BW (band-width) for all the locations of the sensor & actuators on the smart cantilever plant are found out (in our case, it is the 2nd mode of vibration of the smart plant). At that point by utilizing the exact principles for selecting the sampling interval taking into account transmission capacity (BW), around 10 times of the most extreme second vibration mode frequency of the plant has been chosen. τ = 0.0004 secs is taken as the sampling interval. N is taken as the order of the system, i.e., N = 4. Next, the discrete time system (Φ_τ , Γ_τ , C) sampled at a rate of $\frac{1}{\tau}$ is obtained.

The DT systems are controllable & observable. The rank of the system is four. Let initial state be x = E, N = 4, Δ = 0.0002, q = 1200, ε =120, γ = – 0.005. The switching surface is then designed as per the sliding mode control concepts. c is obtained by arbitrarily assigning the Eigen values of $\left[\Phi_{11} - \Phi_{12}\,\bar{c}^{T}\right]$ is inside the circle of unity using *place* command in Matlab software. The surface (switching) is the given by as $s_4(k) = A_1 x_1(k) + A_2 x_2(k) + A_123 x_3(k) + A_4 x_4(k)$. The width of the semi sliding mode band, inside which the framework state stays in consistent state (stable condition) is given by $2\delta \le \frac{2\varepsilon\tau}{2 - q\tau}$ & is found to be within the limitation bounds [61] – [70].

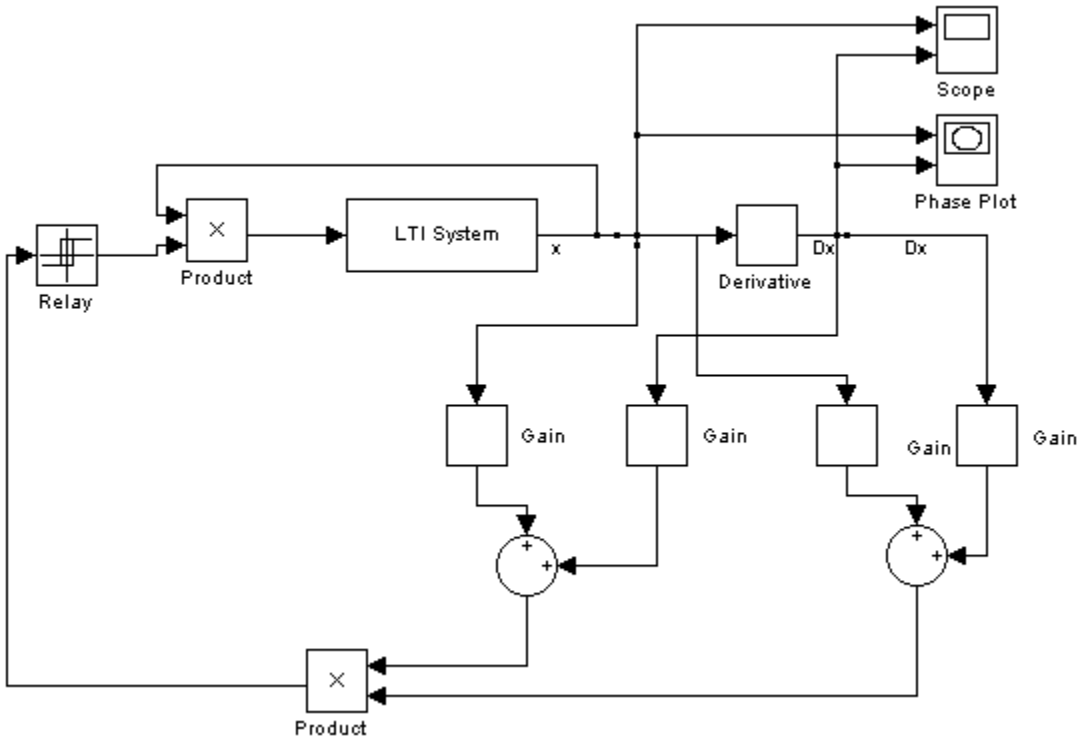


Fig. 2 : Control methodology used for vibration suppression by Simulink diagram

Since the ideology of reaching law is used, hence, the o/p f/b gain is obtained which can be used for the controller design. The simulation results of the plots of the 4 states, viz., x_1, x_2, x_3, x_4, sliding surface, etc… is shown in the results below, which thus shows the effectiveness of the method used to curb down the vibrations. From the simulated results it can be watched that the o/p settles rapidly once the control impact is on. In order to guarantee the concept of sliding phenomenon in the SMC, the reaching law principle is used in the control of smart plants. This o/p f/b based SMC methodology is easy to develop, since the design is centered on the o/p f/b & because of the output feedback action, the stability is guaranteed in no time once the control effort comes into picture. A Simulink block diagram is developed in the Matlab-Simulink environment to curb the vibrations of the plant & is shown in figure below with the title, "Control methodology used for vibration suppression by a Simulink diagram" [70].

III. SIMULATION RESULTS & JUSTIFICATIONS

Simulations are performed in Matlab, the controller when put in feedback with the smart system, showed following results when the controller program is run. Plot of the states, switching surface, sensor outputs, control effort used, etc…. are shown in the Figs. 3 – 6 respectively.

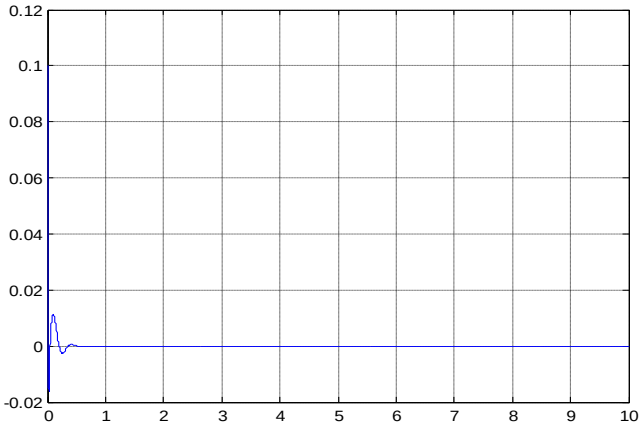


Fig. 3 : DT output based SMC result-1

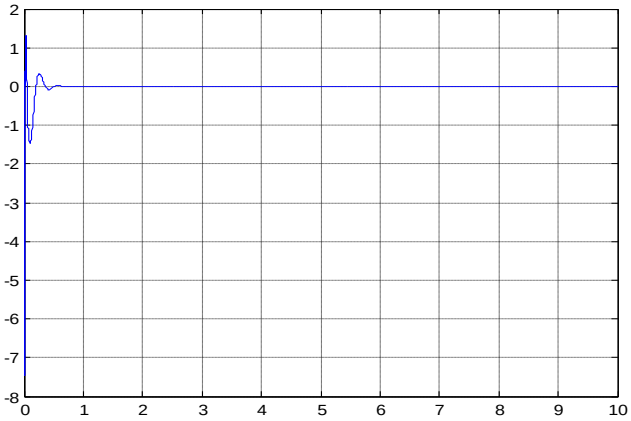


Fig. 4 : DT output based SMC result-2

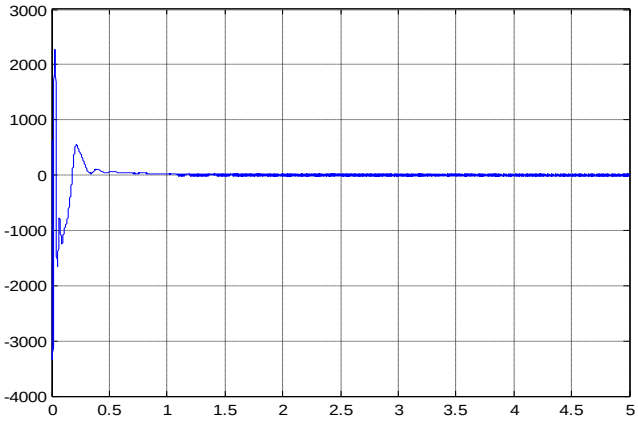


Fig. 5 : DT output based SMC result-3

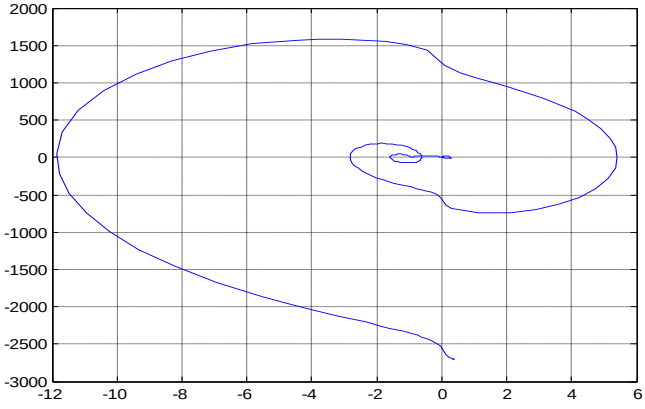


Fig. 6 : DT output based SMC result-4

IV. CONCLUSIONS

In this paper, control of vibrations in smart intelligent structures for a SISO case using discrete output feedback sliding mode control is presented. The simulation results show the effectiveness of the method developed for vibration suppression. Responses are also simulated for the plant with & without control and are compared with the control to show the control effect. It was inferred that without control the transient response was predominant and with control, the vibrations are suppressed & the system states reach the state states very quickly and the vibrations decay out in no time.

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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. (17 yrs), PG Coordinator, Prof-i/c HOD-Prof. & Head (> 2 yrs), 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, Rashtriya Vidya Gaurav 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 7th IETE ICONRFW & the 28th 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 (9th / 3rd 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 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….

