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FOS control of smart intelligent structures for an hollow composite beam

[1]**Mr. Arunkumar G.**, B.E., M.Tech., (Ph.D.-VTU)
[1]Research Scholar doing Ph.D.,
Visvesvaraya Technological University (VTU)-Belgaum,
Karnataka, India
[2]**Dr. T.C.Manjunath**, B.E., M.E., Ph.D. (IIT Bombay),
Senior Member IEEE, Fellow IETE, Fellow IE, Chartered Engineer
[2] Principal, Professor, ECE Dept., Nandi Inst. of Tech. & Mgmt. Sciences, Bangalore-45, Karnataka
[2]*tcmanjunath@gmail.com*

Abstract: *This paper features the modeling, design & control of a smart structure using the concept of fast output sampling feedback control law. Collocated piezoelectric patches are bonded as sensor / actuator to the master structure at a certain finite element location on the beam, i.e., nearby the fixed end of the composite box beam. The beam structure is modeled in state space form using the concept of piezoelectric theory, the beam theory and the Finite Element Method. The beam is subjected to an external disturbance (say, impulse or sine or random excitation). FOS controller is designed for the smart composite box beam. 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, the simulation results show the effect of the designed controller.*

Keywords: *FOS, Vibrations, Composite beam, State space theory, Beam theory.*

I. INTRODUCTION

Active vibration control is an important problem in structures. One of the ways to tackle this problem is to make the structure smart, intelligent, adaptive and self-controlling [3]. The main objective of Active Vibration Control (AVC) is to reduce the vibration of a system by automatic modification of the system's structural response. In many situations, it is important to minimize these structural vibrations, as they may affect the stability and performance of the structures. This obviates the need to strengthen the structure from dynamic forces and disturbances in order to minimize the effects of vibrations and enables the development of lighter, often-cheaper structures exhibiting superior performance. Thus, the vibration control of any system (say, for example, a composite beam) is always a formidable challenge for any control system designer. Composites are being used widely as construction materials in aircraft industries because of their high strength to weight ratio, increased fatigue life and improved damage tolerance characteristics [1].

Thin walled structures are integral parts of an aircraft. In many cases (rotor blades, wing spars etc), they can be modeled as one-dimensional beams, as the sectional dimensions are much smaller compared to the length. Several non-classical behaviors are exhibited by thin walled composite structures, which include the effect of elastic coupling, transverse shear deformation and restrained torsional warping. These characteristics can be successfully exploited for various aircraft applications. Normally, 1D modeling is sufficient to capture the essential features of the box beam. 1D approximations are associated with the assumption of local displacements in terms of generalized beam displacements, namely extension, bending in two directions, shear in two directions and twist [2].

In the present paper, a composite thin walled beam element with surface mounted PZT patches with open and closed contours developed in [4], [8] is used for vibration control purposes. The element uses higher order interpolating polynomials that are derived by solving the electromechanically coupled static homogeneous governing differential equations and hence gives an exact elemental mass and stiffness matrix [18]. Each node has six degrees of freedom (DOF), which include extension, two bending degrees of freedom in span wise and chord wise directions, corresponding rotations and twist. First-order beam theory is used for modeling transverse shear deformation and out-of-plane torsional warping is modeled using Vlasov theory [3].

The paper is organized as follows. Section II gives a overview into the modeling technique of the composite box beam. First, the governing equations for a thin walled beam of certain cross section with PZT patches are derived using the Hamilton's principle. The finite element formulation is presented in next section, followed by the model order reduction scheme and the development of the state space model. A brief review of the controlling technique, viz., the periodic output feedback control technique and the design of the FOS controller is presented in section 5. The simulation results are presented in section 6, followed by the concluding section, acknowledgements and the references, author biographies.

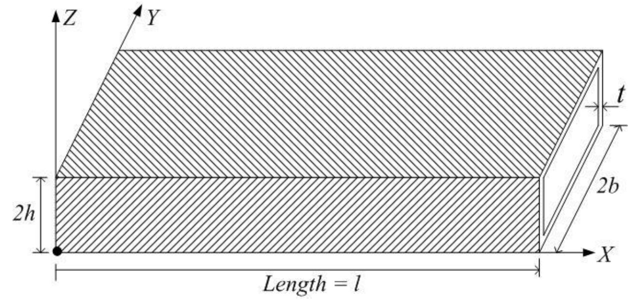
II. MATHEMATICAL MODELLING OF SMART CANTILVER COMPOSITE BEAM

A glass-epoxy box beam with 2 surface mounted PZT patches is used for the vibration suppression of the bending modes. The material properties and dimensions of the box beam and the PZT patches is given in Table I. The cantilever box beam has a ply lay up of [0_3 / 90_2 / 0_3] on all the 4 sides as shown in Fig. 1. The governing differential equation for a smart thin walled composite box beam is obtained as follows. From the geometrical consideration and assuming in-plane deformation to be negligible, the local shell displacements *u*, *v*, and *w* can be written as [4] [18] [82]

$$w = v_0 z_s - w_0 y_s - q\psi \;,\; v = v_0 y_s - w_0 z_s - r\psi \quad (1)$$

$$u = u_0 z_s - z\,\theta_z - \varphi\psi_x \quad (2)$$

where u_0, v_0, w_0 are the displacements in *x, y, z* directions. ψ, θy, θz are the rotations about the *x, y, z* directions. The torsional warping function φ is expressed [4] [18] as



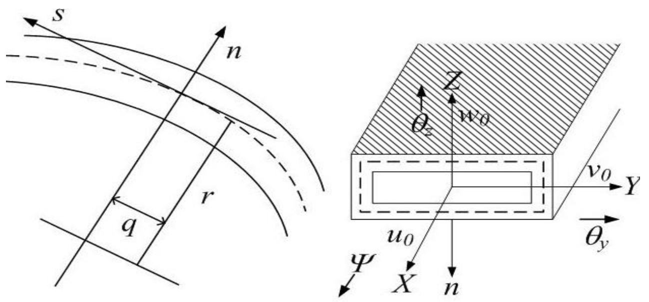


Fig. 1 A thin walled composite box beam and the coordinate systems with their generalized beam displacements

TABLE I. Properties of the glass-epoxy composite box beam [0_3 / 90_2 / 0_3] and the piezoelectric patches (sensor / actuator)

Parameter (with units)	Symbol	Numerical values
Length (m)	l_b	0.655
Width (m)	b	0.057
Thickness (mm)	t_b	0.0005
Young's modulus (GPa)	E_b	62
Poison's ratio	ν	0.31
Density (kg/m^3)	ρ_b	7400
Piezo strain constant (m /V)	$d_{31} = d_{32}$	-166×10^{-12}
	d_{33}	360×10^{-12}
Modulus of rigidity (GPa)	G	3.37

$$\varphi = -\int_0^s r\,ds + 2A_c\frac{\delta_{os}}{\delta}\;;\;\delta_{os} = \int_0^s \frac{ds}{G\,t}\;;\;\delta = \oint \frac{ds}{G\,t} \quad (3)$$

for a closed cross section where *t* is the wall thickness, A_c is the cross sectional area enclosed by the mid-line contour, *G* is the shear modulus, *r* is the radius, *s* is the tangential coordinate and *n* stands for the normal coordinates. Strain - displacement relations are derived using Eqs. (1) - (3) are given by [5] [82]

$$\varepsilon_{xx} = \partial u/\partial x = u_{o,x} + z\,\theta_{y,x} + y\,\theta_{z,x} + \varphi\psi_{xx} \quad (4)$$

$$\gamma_{xs} = \partial u/\partial s = \partial v/\partial x = \gamma_{xs}^s + \gamma_{xs}^t \quad (5)$$

$$\gamma_{xn} = \partial u/\partial n = \partial w/\partial x = \gamma_{xn}^s + \gamma_{xn}^t \quad (6)$$

where ε_{xx} is the normal strain, γ_{xs}, γ_{xn} and are the shear strains. γ_{xn}^t, the tangential component of the shear strain, can be neglected as torsional displacements do not contribute to the shear strain in that direction and hence the transverse shear γ_{xn} can be assumed to contain only γ_{xn}^s components. The 3D linear constitutive relation for the layer containing the PE patch is given by $\{\sigma\} = [Q]\{\varepsilon\} - [e]\{E\}$, where the stresses, strains & electric fields are given by [6] [18] [82]

$$\{\sigma\} = \{\sigma_{xx}, \sigma_{ss}, \sigma_{nn}, \tau_{sn}, \tau_{xn}, \tau_{xs}\},$$
$$\{\varepsilon\} = \{\varepsilon_{xx}, \varepsilon_{ss}, \varepsilon_{nn}, \gamma_{sn}, \gamma_{xn}, \gamma_{xs}\},$$
$$\{E\} = \{E_x, E_s, E_n\}.$$

Here, $[Q]$ is the stiffness matrix and $[e]$ is the piezoelectric constant [2] given in terms of the piezoelectric coefficient $[d]$ as [7]

$$\begin{bmatrix} 0 & 0 & e_{31} \\ 0 & 0 & e_{32} \\ 0 & 0 & e_{33} \\ 0 & e_{24} & 0 \\ e_{15} & 0 & 0 \\ 0 & 0 & e_{36} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & 0 & 0 & Q_{16} \\ Q_{21} & Q_{22} & Q_{23} & 0 & 0 & Q_{26} \\ Q_{31} & Q_{32} & Q_{33} & 0 & 0 & Q_{36} \\ 0 & 0 & 0 & Q_{44} & Q_{45} & 0 \\ 0 & 0 & 0 & Q_{54} & Q_{55} & 0 \\ Q_{61} & Q_{62} & Q_{63} & 0 & 0 & Q_{66} \end{bmatrix} \times \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & d_{36} \end{bmatrix} \quad (7)$$

The piezoelectric coefficient d_{ij} corresponds to the strain in the *j* direction due to an electric field applied in the *i* direction. Here, *j* = {1, 2, 3, 4, 5, 6} refer to directions {*x, s, n, sn, xn, xs*} and *i* = {1, 2, 3} refer to directions {*x, s, n*}. For a passive layer, the parts of the constitutive equation containing electric field terms are not considered. The relation used for sensing mechanical strains through piezoelectric patches is given by [82]

$$[D] = [e]^T\{\varepsilon\} + \{\xi\}[E],$$

where

$$[D] = \{D_x, D_s, D_n\}$$

are the electrical displacements and $[\xi]$ is the permittivity matrix given by [8] [82]

$$[\xi] = \begin{bmatrix} \xi_{11} & 0 & 0 \\ 0 & \xi_{22} & 0 \\ 0 & 0 & \xi_{33} \end{bmatrix}. \quad (8)$$

In the plane stress conditions, the normal stress σ_{ss} and the transverse shear stress τ_{sn} are assumed to be zero and the constitutive model is obtained through the plane stress reduction of the 3D constitutive law considering the electric field $(E_n = E)$ only in the n direction as [1] [82]

$$\begin{Bmatrix} \sigma_{xx} \\ \tau_{xs} \\ \tau_{xn} \end{Bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{16} & 0 \\ \bar{Q}_{16} & \bar{Q}_{66} & 0 \\ 0 & 0 & \bar{Q}_{55} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \gamma_{xs} \\ \gamma_{xn} \end{Bmatrix} - \begin{bmatrix} \bar{e}_{31} \\ \bar{e}_{36} \\ 0 \end{bmatrix} E. \quad (9)$$

The stiffness coefficients $\bar{Q}_{ij}$ are given by

$$\bar{Q}_{11} = Q_{11} - \frac{Q_{12}^2}{Q_{22}}, \ \bar{Q}_{16} = Q_{16} - \frac{Q_{12}Q_{26}}{Q_{22}}, \quad (10)$$

$$\bar{Q}_{66} = Q_{66} - \frac{Q_{26}^2}{Q_{22}}, \ \bar{Q}_{55} = Q_{55} - \frac{Q_{45}^2}{Q_{44}}, \quad (11)$$

where Q_{ij} are the transformed stiffness coefficients. The piezoelectric constants $\bar{e}_{ij}$ are given by [9]

$$\bar{e}_{31} = e_{31} - \frac{Q_{12}}{Q_{22}} e_{32}, \ \bar{e}_{36} = e_{36} - \frac{Q_{26}}{Q_{22}} e_{32}. \quad (12)$$

The total strain, electrical and kinetic energies are calculated using the expressions [10] [18]

$$\Pi = \frac{1}{2}\int_0^L \int_A (\sigma_{xx}\varepsilon_{xx} + \tau_{xs}\gamma_{xs} + \tau_{xn}\gamma_{xn})\,\mathrm{d}A\,\mathrm{dx} \quad (13)$$

$$\Pi_E = -\frac{1}{2}\int_0^L \int_A (E\,D)\,\mathrm{d}A\,\mathrm{dx} \quad (14)$$

$$T = \frac{1}{2}\rho\int_0^L \int_A (\dot{u}^2 + \dot{v}^2 + \dot{w}^2)\,\mathrm{d}A\,\mathrm{dx} \quad (15)$$

where d*A* is the elemental area given by d*s* d*n*. Using Hamilton's principle, the minimization of the above energy with respect to the six mechanical degrees of freedom $u_0, v_0, w_0, \psi, \theta_y, \theta_z$ and one electrical degree of freedom *E* will give 7 electromechanically coupled differential equations [8]. These governing equations and the associated boundary conditions will be used for stiffness and electromechanical coupling matrix formulation. This is done by assuming appropriate polynomials for the displacement field based on the order of the static part of the differential equations and substituting these back into the governing equations. In this process, certain constants can be eliminated and, at the same time, certain constants become dependent on material and sectional properties [7] [82].

III. FINITE ELEMENT FORMULATION

The formulated smart beam element has the super convergence property as it uses exact solutions to the electromechanically coupled governing equations as its interpolation functions. Hence, for point loads, one element between any two discontinuities is sufficient to capture the exact response for static analysis. This results in a substantial reduction in the system size. For dynamic analysis, a consistent mass matrix formulated on the basis of the interpolation functions is used [11] [82].

As a result, for a given discretization, the accuracy of the present formulation is expected to be superior compared to that of elements formulated on the basis of the conventional polynomial approximation. This is because the stiffness of the structure, which is exactly represented, is prone to higher error if an approximate polynomial is used in its formulation as is done in the conventional formulation [12].

Hence, good accuracy in dynamic analysis can be expected from this element using smaller system sizes. The finite element formulation [4], [6], [8] begins by assuming the interpolating functions of appropriate order for the six mechanical degrees of freedom. Looking at the governing equations [8], we see that the axial displacement u_0 and the slopes about the y and z axes (θy and θz) require quadratic polynomials, while the lateral and transverse displacements v_0 and w_0 and the twist (ψ) degrees of freedom require cubic polynomials. Hence the interpolating polynomials for the six degrees of freedom can be assumed as [4], [8]

$$u_0(x) = a_1 + a_2 x + a_3 x^2,$$

$$v_0(x) = a_4 + a_5 x + a_6 x^2 + a_7 x^3, \quad (16)$$

$$w_0(x) = a_8 + a_9 x + a_{10} x^2 + a_{11} x^3, \quad (17)$$

$$\psi(x) = a_{12} + a_{13} x + a_{14} x^2 + a_{15} x^3, \quad (18)$$

$$\theta_y(x) = a_{16} + a_{17} x + a_{18} x^2,$$

$$\theta_z(x) = a_{19} + a_{20} x + a_{21} x^2. \quad (19)$$

The governing differential equations are electro-mechanically coupled having higher order derivatives of the electric field (E). In all, the interpolating polynomials for displacements having 21 constants are evaluated using the boundary conditions of the composite beam, finally leading to the shape functions corresponding to the 6 displacement fields as [13]

$$[N] = \begin{bmatrix} N_u & N_v & N_w & N_\psi & N_{\theta_y} & N_{\theta_z} \end{bmatrix} \quad (20)$$

The electric field E can be expressed in terms of the nodal displacement vector as $E = [K_s]\{u\}_e$. This equation relates electric field to the nodal displacement $\{u_e\}$ and is used for sensing application. The nodal force vector is given by $F + [K_A]$ E = $[K]\{u_e\}$, where $[K_A]$ is an electro-mechanical coupling matrix which gives the expression for the actuating force due to the electric field E applied to the PZT patch and $[K]$ is the exact stiffness matrix, that is derived from the polynomials that exactly satisfy the governing differential equations. The consistent mass matrix is formulated using the material dependent shape functions and is given by [14]

$$[M] = \int_0^L \int_A \rho [N]^T [I]^T [I][N] \mathrm{d}n \ \mathrm{d}s \ \mathrm{d}x. \quad (21)$$

The matrix $[I]$ obtained from Eqs. (1) - (3) is [4], [8]

$$[I] = \begin{bmatrix} 1 & 0 & 0 & \varphi & z & y \\ 0 & y_s & z_s & r & 0 & 0 \\ 0 & z_s & -y_s & -q & 0 & 0 \end{bmatrix}. \quad (22)$$

Depending on the geometry of the cross section, many of the constants in the mass matrix formulated above vanish, resulting in a simpler form. The damping matrix is obtained as [15] [80]

$$C = \alpha M + \beta K, \quad (23)$$

where α and β are structural constants of composite box beam. In the above discussions, M and K are called as the local mass and stiffness matrices. The equation of motion for a system with n DOF is finally given by

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F} \quad (24)$$

where **M**, **C** and **K** are the assembled mass, damping and the assembled stiffness matrices (called as the global matrices). These are obtained by the assembling techniques used in the finite element method. Here, $\ddot{\mathbf{x}}$, $\dot{\mathbf{x}}$ and $\mathbf{x}$ are the accelerations, velocities and displacements of the full system, **F** is the force coefficient vector. The displacement vector **x** of the full system contains all the nodal displacements $u_{0_i}, v_{0_i}, w_{0_i}, \psi_i, \theta_{y_i}, \theta_{z_i}$ at each node. Using the equation of motion from Eq. (24), the state space model of the system is obtained as [16] [80]

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + Bu(t) + Er(t),$$
$$y(t) = C\mathbf{x}(t), \quad (25)$$

where

$$A = \begin{bmatrix} 0 & I \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}_{(120 \times 120)}, \ B = \begin{bmatrix} 0 \\ \mathbf{M}^{-1}\mathbf{F} \end{bmatrix}_{(120 \times 1)}, \quad (26)$$

where A, B, C, E are the system matrix, input matrix, output matrix and the external disturbance matrix which couples the disturbance to the system. The output of the system is taken as the tip displacement.

IV. MODEL ORDER REDUCTION

Before you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads—the template will do that for you.

In many engineering problems, efficient reduction or condensation schemes are required to not only reduce the model size and decrease the computational time, but also to retain only the measurable degrees of freedom from the full analytical model. In the above case, the order of the system obtained was fairly high, i.e., 120, therefore, before we apply any control strategy, a reduced model [17] for the above system needs to be obtained.

Thereafter, model order reduction is carried out eliminating the fast modes. For model order reduction, we use Marshall technique [17] wherein, the system is decoupled into faster and slower modes and then derivative of the states corresponding to faster modes is set to zero and then solve for the remaining states. This method ensures that the response of the reduced order model has correct steady state values and still maintains satisfactory dynamic behavior. Considering a continuous time model given by [82]

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u,$$

$$y = \begin{bmatrix} C_1 & C_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + D u,$$

The system is transformed to $x = T z$, to get the transformation relation [80]

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = Z = T^{-1} x = Q x = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

to obtain

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} \Lambda_1 & 0 \\ 0 & \Lambda_2 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} \Gamma_1 \\ \Gamma_2 \end{bmatrix} u, \qquad (27)$$

Here sub matrix Λ_1 is associated with slower modes, whereas the response of the elements in Λ_2 settles very fast and thus may be approximated to a instantaneous step change. Therefore, the derivative of z_2 is set to zero and the resulting equation is solved for z_1. The reduced order model finally is given by [17]

$$\dot{x}_1 = T_{11} \Lambda_1 T_{11}^{-1} x_1 + \left[B_1 - A_{12} Q_{22}^{-1} \Lambda_2^{-1} \Gamma_2 \right] u,$$

$$y = \left[C_1 - C_2 Q_{22}^{-1} Q_{21} \right] x_1 + \left[D - C_2 Q_{22}^{-1} \Lambda_2^{-1} \Gamma_2 \right] u, \qquad (28)$$

In our reduced model, we eliminate the faster modes and thereby obtain a reduced order model of order 8. The disturbance is being induced via the E matrix and the control is given through the B matrix. The natural frequencies obtained are 34.46, 81.32, 206.59 and 465.13 Hz. Model validation is done in commercially available softwares like the PATRAN and the NASTRAN. The obtained reduced order state space model is [80]

$$A = \begin{bmatrix} -1.9 & 230 & -4.3 & -5.1 & -3.4 & -4 & 3.8 & -0.4 \\ -230 & -1.8 & 4.7 & 4.7 & 3.4 & 4 & -3.8 & 0.4 \\ -4.3 & -4.7 & -60.4 & -1421.9 & -95.1 & -103.5 & 98.9 & -10.4 \\ 5.1 & 4.7 & 1421.9 & -80.3 & -103.5 & -134.4 & 125.4 & -12.1 \\ 3.4 & 3.4 & 95.1 & -103.5 & -661.7 & -4418.4 & 2575.1 & -106.8 \\ -4 & -4 & -103.5 & 134.4 & 4418.4 & -1440.4 & 1642.6 & -726 \\ 3.8 & 3.8 & 98.9 & -125.4 & -2575.1 & 1642.6 & -1956.4 & 7144.8 \\ 0.4 & 0.4 & 10.4 & -12.1 & -106.8 & 726 & -7144.8 & -21.1 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.008 \\ 0.0078 \\ 0.0096 \\ -0.0105 \\ -0.0072 \\ 0.0085 \\ 0.008 \\ -0.0008 \end{bmatrix}, \quad C^T = \begin{bmatrix} -0.008 \\ 0.0078 \\ -0.0096 \\ -0.0105 \\ -0.0072 \\ -0.0085 \\ 0.008 \\ -0.0008 \end{bmatrix}, \quad D = 0, \qquad (29)$$

which is used further for the FOSFB controller design.

V. FOS CONTROLLER DESIGN

The control strategy for the SISO representation of the developed smart composite beam model using the fast output sampling feedback control law with 1 actuator input u and 1 sensor output y. Simulations are done in Matlab as well as in Simulink. The open loop response, closed loop, the control input required to damp out the vibrations are observed and are shown in the figures below. The sensor is used to sense the vibrations in the beam and send to the controller, where the signals are evaluated and corresponding destructive signals to curb down the vibrations are calculated by the controller. Finally, this is given as input to the actuator will induces destructive anti-vibration signals in the beam to reduce the overall vibration signature of the beam.

In this paper, a FOS control is presented for the hollow beam model to suppress the vibration of the smart flexible cantilever beam by considering the first two vibration modes. The control law thus obtained is of practical importance. Responses are also simulated for the plant 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. It was seen that the tip displacement is well controlled and is within limits. The designed controller requires constant gains and hence may be easier to implement in real time. Some of the responses along with the control input are shown below in the Figs. 3 to 7 respectively.
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 [11] [13]. The graphical

illustration of the fast output sampling feedback control law is shown in Fig. 2 as

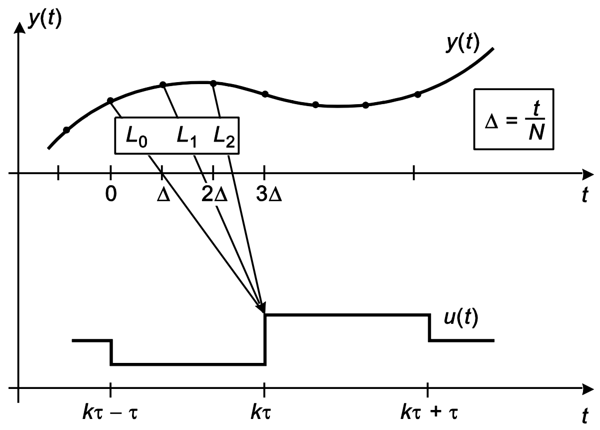


Fig. 2 : FOS method (graphical illustration)

In the accompanying area, we add to the control technique for the MIMO representation of the created brilliant structure model utilizing the quick yield testing criticism control law created by Werner and Furuta [76], [77], [78] with 2 actuator i/p's u_1, u_2, and 2 sensor o/p's y_1, y_2, for the created multivariable plant as appeared in figure 4. Ordinarily, as the complete state vector is not accessible for input, the configuration of a state spectator is not a clear answer for multivariable and multimodel issues either. In the event that the controller is to be actualized digitally on a PC, then an examined information controller must be outlined at any rate, and in this segment it is demonstrated how a strong inspected information state input pick up with zero-request hold can be acknowledged by a FOS f/b controller.

In this sort of control law as appeared in Fig. 2 [76], [77], [78], the estimation of the info at a specific minute relies on upon the yield esteem at once preceding this minute (in particular toward the start of the period). Werner and Furuta [76], [77], [78] have demonstrated that the poles of the discrete time control framework could be doled out subjectively (inside of the normal limitation that they ought to be found symmetrically w.r.t. real axes) utilizing the quick yield inspecting strategy. Since the criticism increases are piecewise constants, their technique could without much of a stretch be actualized, ensures the shut circle soundness and showed another probability. Such a control law can balance out a much bigger class of frameworks. The control goal is to test the o/p $y(t)$ at a speedier rate, i.e., at interims of Δ and connected to the controller at interim values of τ which is more worthwhile. In the meantime, the states are not required for f/b purposes in the FOS case and here, we are going to design the state f/b using the o/p f/b.

Consider a plant described by a LTI state mathematical space model given by

$$\dot{x}(t) = A x(t) + B u(t), \quad y(t) = C x(t),$$

where $x \in \Re^n$, $u \in \Re^m$, $y \in \Re^p$, $A \in \Re^{n\times n}$, $B \in \Re^{n\times m}$, $C \in \Re^{p\times n}$, A, B, C, are constant matrices of appropriate dimensions and it is assumed that the model is controllable and observable. Assume that output measurements are available at time instants $t = k\,\tau$, where $k = 0, 1, 2, 3, \ldots$. Now, construct a discrete linear time invariant system from these output measurements at sampling rate $\frac{1}{\tau}$ (sampling interval of τ secs) during which the control signal u is held constant. The system obtained so is called as the τ system and is given by

$$x((k+1)\tau) = \Phi_\tau\, x(k\tau) + \Gamma_\tau\, u(k\tau), \quad y(k\tau) = C\, x(k\tau),$$

where $\Phi_\tau, \Gamma_\tau, C$ are constant matrices of appropriate dimensions. Assume that the plant is to be controlled by a digital computer, with sampling interval τ and zero order hold and that a sampled data state feedback design has been carried out to find a state feedback gain F such that the closed loop system

$$x(k\tau + \tau) = (\Phi_\tau + \Gamma_\tau F)\, x(k\tau)$$

has desirable properties.

Let $\Delta = \frac{\tau}{N}$, where $N >$ the observability index υ of the system. The control signal $u(k)$, which is applied during the interval $k\tau \le t \le (k+1)\tau$ is then generated according to

$$u(k) = \begin{bmatrix} L_0 & L_1 & \ldots\ldots & L_{N-1} \end{bmatrix} \begin{bmatrix} y(k\tau - \tau) \\ y(k\tau - \tau + \Delta) \\ : \\ : \\ y(k\tau - \Delta) \end{bmatrix} = L\, y_k$$

,

where the matrix blocks L_j represent the output feedback gains and the notation L, y_k has been introduced here for convenience. Note that $\frac{1}{\tau}$ is the rate at which the loop is closed, whereas the output samples are taken at the times N - times faster rate $\frac{1}{\Delta}$. To show how a FOS controller can be designed to realize the given sampled data state feedback gain for a controllable and observable system, we construct a fictitious, lifted system for which the above equation can be interpreted as static output feedback [Syrmos]

Let (Φ,Γ,C) denote the system sampled at the rate $\frac{1}{\Delta}$. Consider the discrete time system having at time $t=k\tau$, the input $u_k=u(k\tau)$, the state $x_k=x(k\tau)$ and the output y_k as

$$x_{k+1}=\Phi_\tau x_k+\Gamma_\tau u_k\,,\quad y_{k+1}=\mathbf{C}_0 x_k+\mathbf{D}_0 u_k\,,$$

where

$$\mathbf{C}_0=\begin{bmatrix} C \\ C\Phi \\ \vdots \\ C\Phi^{N-1}\end{bmatrix};\ \mathbf{D}_0=\begin{bmatrix} 0 \\ C\Gamma \\ \vdots \\ C\sum_{j=0}^{N-2}\Phi^j\Gamma\end{bmatrix}.$$

Now, design a state feedback gain F such that $(\Phi_\tau+\Gamma_\tau F)$ has no Eigen values at the origin and provides the desired closed loop behavior, i.e., the system is stable, the Eigen values are placed inside the unit circle (using the pole placement technique) in such a position that the closed loop response with the state feedback settles quickly and the vibrations are damped out in a quicker time. Then, assuming that in the interval $k\tau\le t\le(k\tau+\tau)$,

$$u(t)=F\,x(k\tau),$$

one can define the fictitious measurement matrix,

$$\mathbf{C}(F,N)=(\mathbf{C}_0+\mathbf{D}_0F)(\Phi_\tau+\Gamma_\tau F)^{-1},$$

which satisfies the fictitious measurement equation

$$y_k=\mathbf{C}\,x_k.$$

For L to realize the effect of F, it must satisfy the equation.

$$\mathbf{LC}=F.$$

Let υ denote the observability index of (Φ,Γ,C). It can be shown that for $N\ge\upsilon$, generically $\mathbf{C}$ has full column rank, so that any state feedback gain can be realized by a fast output sampling gain $\mathbf{L}$. If the initial state is unknown, there will be an error $\Delta u_k=u_k-F\,x_k$ in constructing the control signal under the state feedback; one can verify that the closed-loop dynamics are governed by

$$\begin{bmatrix} x_{k+1} \\ \Delta u_{k+1}\end{bmatrix}=\begin{bmatrix}\Phi_\tau+\Gamma_\tau F & \Gamma_\tau \\ 0 & \mathbf{LD}_0-F\,\Gamma_\tau\end{bmatrix}\begin{bmatrix} x_k \\ \Delta u_k\end{bmatrix}.$$

The system in the above equation is stable if stabilizes only if (Φ_τ,Γ_τ) and the matrix $(\mathbf{LD}_0-F\,\Gamma_\tau)$ has all its Eigen values inside the unit circle. It is evident that the eigen values of the closed loop system under a FOS control law are those of $(\Phi_\tau+\Gamma_\tau F)$ together with those of $(\mathbf{LD}_0-F\,\Gamma_\tau)$. This suggests that the state feedback F should be obtained so as to ensure the stability of both $(\Phi_\tau+\Gamma_\tau F)$ and $(\mathbf{LD}_0-F\,\Gamma_\tau)$. The problem with controllers obtained in this way is that, although they are stabilizing and achieve the desired closed loop behavior in the output sampling instants, they may cause an excessive oscillation between sampling instants. The fast output sampling feedback gains obtained may be very high. To reduce this effect, we relax the condition that $\mathbf{L}$ exactly satisfy the linear equation and include a constraint on the gain $\mathbf{L}$.

Thus, we arrive at the following as

$$\|\mathbf{L}\|<\rho_1;\ \|\mathbf{LD}_0-F\Gamma_\tau\|<\rho_2;\ \|\mathbf{LC}-F\|<\rho_3$$

where represents the upper bounds on the spectral norms of $\mathbf{L}$, $(\mathbf{LD}_0-F\,\Gamma_\tau)$ and $(\mathbf{LC}-F)$. This can be formulated in the form of Linear Matrix Inequalities as

$$\begin{bmatrix}-\rho_1^2 I & \mathbf{L} \\ \mathbf{L}^T & -I\end{bmatrix}<0;\ \begin{bmatrix}-\rho_2^2 I & \mathbf{LD}_0-F\Gamma_\tau \\ (\mathbf{LD}_0-F\Gamma_\tau)^T & -I\end{bmatrix}<0;\ \begin{bmatrix}-\rho_3^2 I & \mathbf{L}C-F \\ (\mathbf{L}C-F)^T & -I\end{bmatrix}<0$$

In this form, the LMI control optimization toolbox is used for the synthesis of $\mathbf{L}$. Here, ρ_1 means low noise sensitivity, ρ_2 small means fast decay of observation error, and most importantly, ρ_3 small means that the FOS controller with gain $\mathbf{L}$ is a good approximation of the originally designed state feedback controller.

If $\rho_3=0$, then $\mathbf{L}$ is an exact solution. If suitable bounds ρ_1,ρ_2 are known, one can keep these bounds fixed and minimize ρ_3 under these constraints. This requires a search for a FOS controller which gives the best approximation of the given state feedback designed under the constraints represented by ρ_1 and ρ_2. It should be noted here that closed loop stability requires $\rho_2<1$, i.e., the eigen values which determine the error dynamics must lie within the unit disc. In this form, the function [*min cx* ( )] of the LMI control toolbox for MATLAB can be used to minimize a linear combination of ρ_1,ρ_2 and ρ_3.

VI. SIMULATION RESULTS

In this section, the Matlab simulation results are presented to depict the control of vibrations of the smart beam when they are subjected to forces. In this section, a single input single output model of the plant is used [1] – [10]. The mathematical model is developed, the

fast output sampling feedback controller is designed, put in loop with the plant, the open loop response, closed loop (with the state feedback gain & the FOS gain L), the control input u required to damp out the vibrations are observed and are shown in the figures below [11] – [20]. From the simulation results, it is observed that when the beam is divided into a number of finite elements, the results with the piezo pair kept at the fixed end (system 1) is more satisfactory than the results with the piezo pair kept at the free end [21] – [30]. The open loop and the closed loop responses are also observed.
From the results, it is observed that without control, the transient response is unsatisfactory & takes more time to settle & with control, the vibrations are suppressed in no time, which shows the control effect [31] – [40]. The control signal along with the tip displacements are also observed through the Matlab simulation results [61] – [70]. From these tip displacement results, it can be observed that with control the tip displacements die at a faster rate than without control [71] – [80].
The beam with the piezo pair kept at the root is touchier to the first mode as the twisting moment is most extreme, strain rate is higher, least tip deflection, better sensor o/p & less prerequisite of the control impact (control will be more compelling at the root) [41] – [50]. The beam with the piezo pair kept at the free end is less sensitive to the 1st mode as the bending moment is min. & the rate of strain is lesser, maximum tip displacement, less sensor o/p and more usage of control effect (at the root, the control will be more predominant) to dampen out the vibrations.
Hence, it is concluded that fixed end model is the best for active vibration control as the output responses with F & L are enhanced & the magnitude of the impulse responses, i.e., of the open loop and the closed loop of both the CTS / DTS is less compared to the free ends [51] – [60]. The bode plot observed from the simulation results also shows that the two modes are well controlled & within limits, the two natural frequencies can be clearly seen [80].

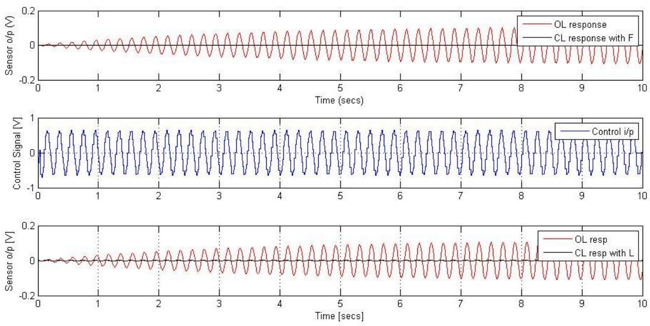


Fig. 3 : Matlab simulation results - 1

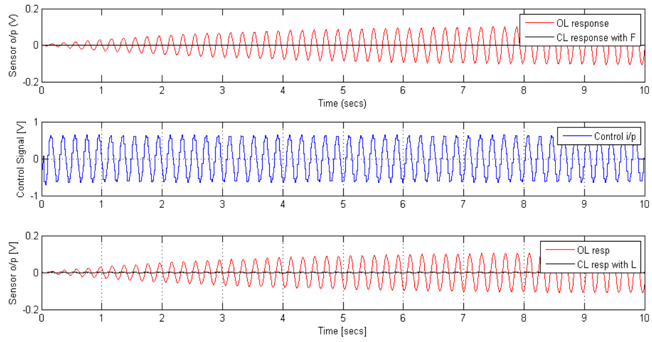


Fig. 3 : Matlab simulation results - 2

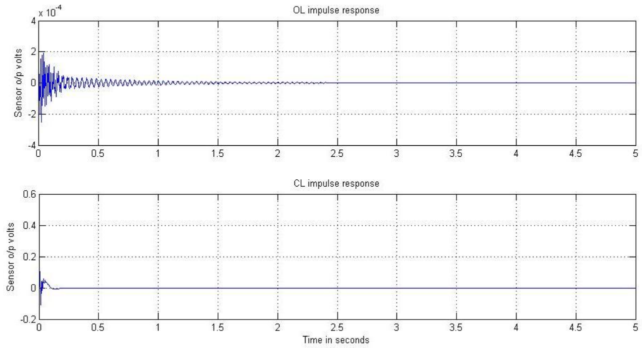


Fig. 3 : Matlab simulation results - 3

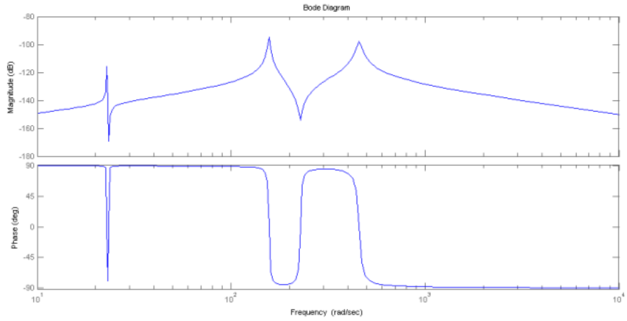


Fig. 3 : Matlab simulation results - 4

Matlab Optimization Command Prompt Results

F =

1.0e+003 *

1.4153 1.0336

Solver for linear objective minimization under LMI constraints

Iterations : Best objective value so far

1
*** new lower bound: -2.980232e+017
2
*** new lower bound: -1.271604e+017
3
*** new lower bound: -4.476925e+016

```
    4
***           new lower bound: -1.583506e+016
    5
***           new lower bound: -5.586499e+015
    6
***           new lower bound: -1.970978e+015
    7
***           new lower bound: -6.953792e+014
    8
***           new lower bound: -2.453372e+014
    9
***           new lower bound: -8.655754e+013
   10
***           new lower bound: -3.053840e+013
* switching to QR
   11
***           new lower bound: -1.077426e+013
   12          1099.616664
***           new lower bound: -3.801262e+012
   13          1099.616664
***           new lower bound: -1.341094e+012
   14          1099.616664
***           new lower bound: -4.730631e+011
   15          1099.616664
***           new lower bound: -1.666500e+011
   16          1099.616664
***           new lower bound: -5.808019e+010
   17         -8.340820e+008
***           new lower bound: -1.842674e+010
   18         -8.340820e+008
***           new lower bound: -7.346244e+009
   19         -9.812443e+008
***           new lower bound: -4.591639e+009
   20         -9.812443e+008
***           new lower bound: -2.600582e+009
   21         -9.988556e+008
***           new lower bound: -1.124780e+009
   22         -9.988556e+008
***           new lower bound: -1.074712e+009
   23         -9.988556e+008
***           new lower bound: -1.006359e+009

 Result:  feasible solution of required accuracy
          best objective value: -9.988556e+008
          guaranteed relative accuracy: 7.51e-003
          f-radius saturation:  99.886% of R = 1.00e+009

L =

  1.0e+003 *

    4.0542   -3.5812   -3.5364    4.1636
```

```
Transfer function:
0.0001006 s^3 + 5.843e-006 s^2 + 0.05742 s + 3.725e-009
------------------------------------------------------
 s^4 + 2.577 s^3 + 2.575e004 s^2 + 2032 s + 1.003e007


zeros_2_num =

  -0.0291 +23.8959i
  -0.0291 -23.8959i
  -0.0000


poles_2_den =

  1.0e+002 *

  -0.0127 + 1.5923i
  -0.0127 - 1.5923i
  -0.0002 + 0.1989i
  -0.0002 - 0.1989i
```

VII. CONCLUSIONS

A mathematical model for the composite box beam formulated in [4], [8] is used for the vibration control purposes in the paper. A two-node beam element with 6 DOF is used to formulate the composite box beam element using beam theory. Then, the state space model is validated by modeling the same beam structure in Msc PATRAN and NASTRAN and thus correlating the natural frequencies obtained by the 2 procedures. The sensor is used to sense the vibrations in the beam and send to the controller, where the signals are evaluated and corresponding destructive signals to curb down the vibrations are calculated by the controller. Finally, this is given as input to the actuator will induces destructive anti-vibration signals in the beam to reduce the overall vibration signature of the beam. Simulations are done in Matlab as well as in Simulink.

Controller has been designed for the composite beam using the FOS control technique for the developed state space model of the smart beam to suppress the first few vibratory modes. The various responses are observed. Responses are also simulated for the plant 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. It was seen that the tip displacement is well controlled and is within limits. The designed FOS controller requires constant gains and hence may be easier to implement in real time using some interfacing cards like dSPACE, TI-TMS-DSP, NI, Data acquisition cards, etc.

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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, 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 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….