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A Boundary Control for a Class of Systems Described by Hyperbolic Partial Differential Equations with Nonlinear Components

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Abstract*—The paper treats the control problem of a class of DPS described by hyperbolic PDE by using a spatial weighted error control. The eigen system of the PDE model is inferred. It is proved that the stability analysis can be obtained by using the finite dimensional model of the eigen system. A control algorithm is proposed and analyzed for a dynamic model with uncertain components. Numerical simulations that illustrate the efficiency of the method are presented.

Index Terms—**Distributed parameter systems, boundary control, weighted error.**

I. INTRODUCTION

The study and development of feedback controllers for Distributed Parameter Systems (DPS) models described by partial differential equations (PDE) represent a very complex problem and a great number of researchers have tried to offer solutions. Boundary control of DPS occupies an important place in control theory and constitutes an active research area. There is a plethora of papers that treats the boundary control for DPS and a chronological list can be found in [1]. A class of these papers treats the spatial discretization of the PDE to derive a set of differential equations that constitute an approximation of the original DPS model [2-4]. Also, for DPS, which are described by hyperbolic PDEs, [5-8] used modal decomposition to derive finite-dimensional systems that capture the dominant dynamics of the original PDE and are subsequently used for the low dimensional predictive controller design. In [9], nonlinear order reduction and control of nonlinear parabolic systems were studied for parabolic PDEs. Other authors treat the PDE model without approximation for the controller design [10-12] and avoid the losing the distributed nature of these systems. Within the class of distributed parameter systems, the solution of LQ control problem for hyperbolic systems by solving an operator Riccati equation was studied [14]. Geometric control has proved to be very successful as a control approach of PDE system and successful applications are reported in literature [15-17]. Designing a control law based on geometric control theory presents the advantage that the PDE model can be used in control design without any approximation, which allows preserving the fundamental control theoretical properties associated with the distributed nature of the model [18].A number of papers treat specific classes of DPS associated with mechanical, thermal or robotic systems. In [24], the regulation of a distributed-parameter flexible beam is considered using variable structure control techniques. In [25-29], a dynamical distributed controller is suggested based on an infinite-dimensional generalization of the second-order sliding mode-control techniques. Other papers [30-33] treat the control problem for a DPS model associated with a hyper-redundant manipulator described by hyperbolic PDE.

The functional analysis or semigroup theory provide the mathematical methodology for this type of problems .This paper treats the control problem of a class of DPS described by hyperbolic PDE by using a simple eigen system based technique. First, the eigen system of the PDE model is inferred by using spatial weighted error techniques. It is proved that the stability analysis can be obtained by using the finite dimensional model of the eigen system. A control algorithm is proposed and analyzed for a dynamic model with uncertain components. Numerical simulations that illustrate the efficiency of the method are presented.

The paper is organized as follows. In Section 2, the dynamic model is presented. Section 3 concerns the formulation of the weighted error control, the eigen system and the design methodology of the controller. Section 4 presents the simulation results. Finally, a Conclusion section ends the article.

II. MODEL DESCRIPTION

We consider a class of infinite-dimensional which is governed by a version of the hyperbolic PDE

$$q_{tt} = a^2 q_{ss} + b\, q_t + c\, q + h(q) \qquad (1)$$

where $q = q(t,s)$, s is a mono-dimensional (1-D) spatial variable, $s \in [0,l]$, $t \geq 0$ is time, q_t represents $(\partial q(t,s))/\partial t$, $q_s = (\partial q(t,s))/\partial s$. and a, b, c are coefficient constants $(a > 0, c > 0, b < 0)$. The system state is$(q, q_t) \in \Gamma \subset (H^1(0,l) x L_2(0,l)$. We assume the following initial conditions

$$q(0,s) = q_0(s)$$

$$q_t(0,s)=q_1(s) \;,(q_0,q_1) \in (H^1(0,l) x L_2(0,l)) \qquad (2)$$

and the boundary conditions

$$q_s(t,0) = 0; \;\; q_s(t,l) = u(t) \qquad (3)$$

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where $u(t)$ is the boundary control variable$\left(u \in L_{2\,loc}(0,\infty)\right)$. $h = h(t,s)$ is the uncertain term that satisfies the condition [27]

$$\|h(t,.)\|_2 \leq M\|q(t,.)\|_2 \quad (4)$$

where$M$ is a positive constant. We consider that PDE (1) with initial and boundary conditions (2), (3) represents a well-posed problem. We used the standard notations: L_2 stands for the Hilbert space and H stands for the Sobolev space.

Such models are often met in a class of mechanical systems and in particular for modeling the flexible link manipulators or hyper-redundant arms. In these cases, a^2 represents the bending stiffness, b is the equivalent damping coefficient, c characterizes the elastic behavior, $h$is given by the gravitational components and the input variable u is represented by the boundary torque of the mechanical systems. Also, the initial condition $q_1(s)$ represents the initial velocity.

We consider a desired state $q^d(s)$, $q^d \in L_2(0,l)$, that satisfies linear model steady state of (1) with boundary conditions (3) and the input u^d

$$a^2 q_{ss}{}^d + c\,q^d = 0 \quad (5)$$

$$q_s^d(0) = 0,\ q_s^d(l) = u^d$$

and we denote by

$$\boldsymbol{e}(t,s) = \begin{bmatrix} e(t,s) \\ e_t(t,s) \end{bmatrix} \quad (6)$$

the error variable ,where

$$e(t,s) = q^d(s) - q(t,s),\ e_t(t,s) = -q_t(t,s)$$

$$\boldsymbol{e} = (e, e_t) \in H^1(0,l) x L_2(0,l).$$

Definition 1: The Weighted Error (W-Error) is the spatial weighted geometric mean of the error variable (6)

$$\tilde{\boldsymbol{e}}(t) = \frac{1}{\bar{\chi}}\int_0^l \chi(s)\,\boldsymbol{e}(t,s)ds,\ \tilde{\boldsymbol{e}} \epsilon\, C^2 \quad (7)$$

where

$$\bar{\chi} = \int_0^l \chi(s)ds$$

and$\chi(s)$ is the spatial weighting function that satisfies the following conditions:

1. It is an eigen function of the spatial operator $\frac{d^2}{dx^2}$,

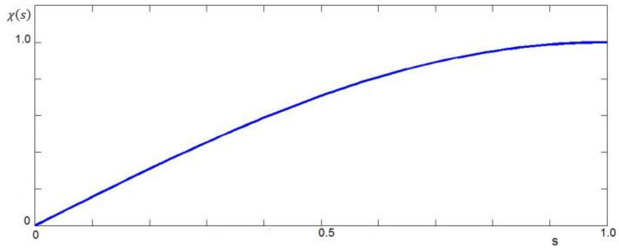

Fig. 1. The weighting function (A=1, l=1)

$$\frac{d^2\chi(s)}{ds^2} = -\lambda\,\chi(s) \quad (8)$$

with boundary conditions

$$\chi(0) = 0\,,\ \frac{d\chi(l)}{ds} = 0 \quad (9)$$

2. $\chi(s) > 0, s \in (0,l]$ (10)

3. It is non-orthogonal with respect to the solutions $q \in \Gamma\ (q \neq 0)$ of (1)-(3),

$$\int_0^l \chi(s)\,q(t,s)ds \neq 0 \quad (11)$$

For example, we consider the weighting function (Fig 1)

$$\chi(s) = A\sin\left(\frac{\pi}{2l}s\right) \quad ,s \in (0,l] \quad (12)$$

with

$$\lambda = \frac{\pi^2}{4l^2} \quad (13)$$

that satisfies the conditions (9)-(11).

Lemma 1: If the spatial weighted error $\tilde{\boldsymbol{e}}(t)$ converges to zero, the system trajectory $q(t,s)$ converges to the desired position $q^d(s), s \in \Omega$.

Proof: For the domain $s \in (0,l]$we obtain,

$$\lim_{t\to\infty}\tilde{\boldsymbol{e}}(t) = \frac{1}{\bar{\chi}}\int_0^l \chi(s)\begin{bmatrix}\left(q^d(s) - q(t,s)\right) \\ -q_t(t,s)\end{bmatrix}ds = 0$$

(14)

and in the virtue of properties (10),(11) ,

$$\lim_{t\to\infty}\left(q^d(s) - q(t,s)\right) = 0,\ s \in (0,l] \quad (15)$$

$$\lim_{t\to\infty}\left(q_t(t,s)\right) = 0 \quad (16)$$

and using (6) results

$$\lim_{t\to\infty}\boldsymbol{e}(t,s) = 0\,,\ \ s \in (0,l] \quad (17)$$

or

$$\lim_{t\to\infty}\|\boldsymbol{e}(t,.)\|_2 = 0 \quad ■ \quad (18)$$

Remark 1: The system stability with respect to $\tilde{\boldsymbol{e}}(t)$ ensures the stability with respect to $\boldsymbol{e}(t,s)$.

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III. CONTROL ALGORITHM

Definition 2: The control task of the system (1)-(3) is to ensure the convergence to the desired state q^d,

$$\lim_{t\to\infty}\|e(t,.)\|_2 = 0$$

Theorem 1: A closed loop control of the system (2.1)-(2.3) is asymptotic stable if the control law is

$$\Delta u(t) = \frac{1}{\chi(l)}(-\chi_s(0)(q^d(0) - q(t,0)) - K_1 \times \int_0^l \chi(s)\,(q^d(s) - q(t,s))ds + K_2 \int_0^l \chi(s)\, q_t(t,s)ds \quad (19)$$

where K_1, K_2 are the positive control coefficients that satisfy the following conditions,

$$(a^2K_2 - b - \alpha) > 0 \quad (20)$$

$$\alpha(a^2K_2 - b - \alpha)(a^2K_1 - (c - a^2\lambda) - M) - \frac{1}{4}(a^2K_1 + \alpha a^2K_2 - \alpha b - 2(c - a^2\lambda) - M)^2 > 0 \quad (21)$$

and α is a positive constant that satisfies

$$(c - a^2\lambda) - \frac{1}{4}\alpha^2 > 0 \quad (22)$$

Proof: From (1)-(3) and (6) the error dynamics will be described by

$$e_{tt} = a^2 e_{ss} + b e_t + ce + h(e) \quad (23)$$

$$e(0,s) = e_0(s), e_t(0,s) = e_1(s) \quad (24)$$

$$e_s(t,0) = 0, e_s(t,l) = \Delta u \quad (25)$$

where,

$$\Delta u = u^d - u \quad (26)$$

(in order to simplify the notation, the variables s,t are omitted). Multiplying Eq (23) by $\frac{\chi(s)}{\bar{\chi}}$ and integrating both sides, we obtain

$$\int_0^l \frac{\chi}{\bar{\chi}} e_{tt}\, ds = \int_0^l (a^2\frac{\chi}{\bar{\chi}} e_{ss} + b\frac{\chi}{\bar{\chi}} e_t + c\frac{\chi}{\bar{\chi}} e + \frac{\chi}{\bar{\chi}} h)ds$$

Integrating by parts, using the boundary conditions (25) and (9), this relation becomes

$$\int_0^l \frac{\chi}{\bar{\chi}} e_{tt}\, ds = \int_0^l (-a^2\lambda\frac{\chi}{\bar{\chi}} + b\frac{\chi}{\bar{\chi}} e_t + c\frac{\chi}{\bar{\chi}} e + \frac{\chi}{\bar{\chi}} h)ds + \Delta u \frac{\chi}{\bar{\chi}}(l) a^2 - a^2 e(l)\frac{\chi_s(l)}{\bar{\chi}} \quad (27)$$

This equation can be rewritten in terms of W-Error variable $\tilde{e}(t)$,

$$\tilde{e}_{tt}(t) = b\tilde{e}_t(t) + (-a^2\lambda + c)\tilde{e}(t + \tilde{h} + \Delta u \frac{\chi}{\bar{\chi}}(l) a^2 + a^2 e(0)\frac{\chi_s(0)}{\bar{\chi}} \quad (28)$$

with initial conditions,

$$\tilde{e}(0) = \tilde{e}_0,\ \tilde{e}_t(0) = \tilde{e}_1 \quad (29)$$

$\tilde{h}(t)$ is obtained from the relation

$$\tilde{h} = \int_0^l \frac{\chi}{\bar{\chi}} h ds \ ,\tilde{h} \epsilon\, C^2 \quad (30)$$

and the constraint (2.4) becomes,

$$|\tilde{h}| \le M|\tilde{e}| \quad (31)$$

Definition 3: We denote the system (28)-(29), defined by the transformation (6), as *"the eigen system of (1)-(3)"*.From Remark 1 we can infer that the dynamic behaviour of the system (1)-(3) is synthesized by the eigen system.
Let us consider the Liapunov function

$$V = V(t) = \frac{1}{2}\tilde{e}_t^{\,2} + \frac{1}{2}(c - a^2\lambda)\tilde{e}^2 + \alpha\,\tilde{e}\tilde{e}_t \quad (32)$$

where α is a positive constant that satisfies the condition (22). The function V can be rewritten as

$$V = \begin{bmatrix}\tilde{e}_t\\ \tilde{e}\end{bmatrix}^T P \begin{bmatrix}\tilde{e}_t\\ \tilde{e}\end{bmatrix} \quad (33)$$

where

$$P = \begin{bmatrix}1 & \frac{\alpha}{2}\\ \frac{\alpha}{2} & (c - a^2\lambda)\end{bmatrix} \quad (34)$$

and the condition (22) ensures that V is positive definite. Taking the derivative of V ,

$$\dot{V} = \tilde{e}_t\tilde{e}_{tt} + (c - a^2\lambda)\tilde{e}\tilde{e}_t + \alpha\,\tilde{e}_t^{\,2} + \alpha\,\tilde{e}\tilde{e}_{tt} \quad (35)$$

By evaluating (35) along with the solutions of (28), substituting the control Δu from (19),rewritten as

$$\Delta u(t) = \frac{1}{\chi(l)}(-\chi_s(0)e(0) - \bar{\chi}(K_1\tilde{e}(t) - K_2\tilde{e}_t(t))) \quad (36)$$

and taking into account the inequality (31), after simple additional manipulations, we obtain

$$\dot{V} \le -\begin{bmatrix}\tilde{e}_t\\ \tilde{e}\end{bmatrix}^T Q \begin{bmatrix}\tilde{e}_t\\ \tilde{e}\end{bmatrix} \quad (37)$$

Where

$$Q = \begin{bmatrix}(-b - \alpha + a^2K_2) & d\\ d & \alpha(a^2K_1 - (c - a^2\lambda) - M)\end{bmatrix} \quad (38)$$

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$$d = \frac{1}{2}\left(-\alpha b - M + \alpha a^2 K_2 + a^2 K_1 - 2(c - a^2\lambda)\right)$$

Taking into account the conditions (20), (21), Q is positive definite. Also, the inequality (37) can be rewritten as the following differential inequality

$$\dot{V} \leq -\frac{\lambda_{min}(Q)}{\lambda_{max}(P)} \begin{bmatrix} \tilde{e}_t \\ \tilde{e} \end{bmatrix}^T P \begin{bmatrix} \tilde{e}_t \\ \tilde{e} \end{bmatrix} = -\frac{\lambda_{min}(Q)}{\lambda_{max}(P)} V \qquad (39)$$

where $\lambda_{min}(Q), \lambda_{max}(P)$ are the minimum and maximum eigenvalue of the matrices, Q and P. This relation proves that the exponential convergence of $\left\| \begin{matrix} \tilde{e}_t \\ \tilde{e} \end{matrix} \right\|$ to zero as $t \to \infty$. Taking into acount the *Lemma 1*, it yields

$$\lim_{t\to\infty} \|\boldsymbol{e}(t,.)\|_2 = 0 \quad \blacksquare \qquad (40)$$

IV. NUMERICAL SIMULATIONS

Consider the dynamic model of a hyper-redundant continuum robotic arm described by PDE model (1)-(4) [30],

$$I_\rho q_{tt} = EI\, q_{ss} + b\, q_t + c\, q + h(q) \qquad (41)$$

$q(0,s) = 0$, $q_t(0,s)=0$

$q_s(t,0) = 0$; $EI\, q_s(t,l) = \tau(t)$

where I_ρ is the rotational inertial density ($I_\rho = 1$), EI is the bending stiffness ($EI = 1.5$), b is the equivalent damping coefficient ($b = -0.5$) , c is the elastic coefficient ($c = 15$). These constants are scaled to realistic ratios for a long thin arm. The initial and boundary conditions are: $q_0(s)$ = 0, $q_1(s)$ =0, $q_s(t,0)$ = 0; $q_s(t,l) = \tau/EI$, where τ is the torque applied at the top of the arm ($s = l = 1$) .The non-linear term h(q) represents the uncertain term defining the gravitational components, $h(q) = \rho g A \int_0^s \cos q\, ds$, whereρ is the linear density, g is gravitational acceleration and A is the section area [29]. For the characteristic values of these parameters ($\rho = 0.1\ kg/m, g = 10\ m/s^2, A = 4\,10^{-4} m^2$), associated to this thin long arm, the inequality (4) is satisfied for M = 10. The weighting function $\chi(s) = A \sin\left(\frac{\pi}{2} s\right)$, $s \in (0,1]$, $\lambda = \frac{\pi^2}{4}$ is selected.The desired state is $q^d(s) = 1.8 \cos(\frac{\pi}{2} s)$ that satisfies the stationary desired state for $\tau^d = -3.8$.Acontrol algorithm for the desired state $q^d(s)$ *is* implemented. The controller gains are selected $k_1 = 40, k_2 = 15$. These values verify the conditions (20)-(21) of the Theorem 1.For solving the PDE governing the closed-loop system behaviour, standard finite-difference approximation method is used by discretizing the spatial solution domain $\in [0,1]$ .The resulting system is implemented in Matlab-Simulink. The boundary control law and the error dynamics are presented in Fig. 2 and Fig. 3, respectively.

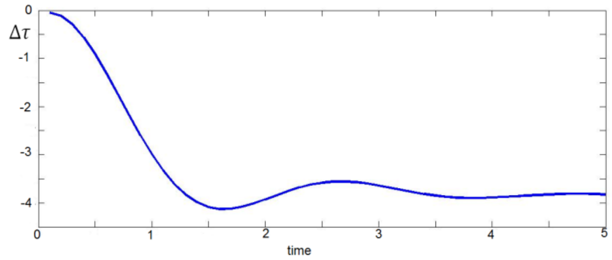

Fig.2.The boundary control

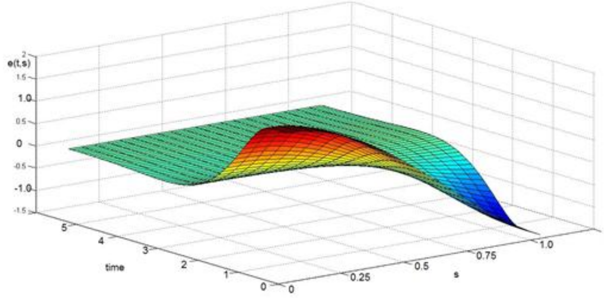

Fig.3. The evolution of the error e(t, s) for $q^d(s) = 1.8 \cos\left(\frac{\pi}{2}\right.$

We remark the good convergence toward zero of the error in the conditions of the presence of a disturbed term$h(s)$.

V. CONCLUSION

This paper treats the control problem of a class of DPS described by hyperbolic PDE with nonlinear component. By using a spatial weighted error control, the eigen system of the hyperbolic model is inferred. We prove that the stability analysis can be obtained by using the finite dimensional model of the eigen system. For the future, we intend to develop this result for other classes of DPS.

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Volume 3, Issue 5, November 2013

projects in the field of embedded systems for neurorehabilitation dealing with neuroprosthesis control algorithms. In her research activity, she is also interested in grasping control algorithms and hyper-redundant systems and she has analyzed the control problem of the hyper-redundant arms that perform the grasping function by coiling, studying the dynamic model of the continuum arm for the position control.

DecebalPopescu is associate professor at University Politehnica of Bucharest since 2008. He received his Bachelor of Engineering in 1998 at UPB, Computer Science Department, followed by M.Sc at the same department. In 2003, he became PhD in Computer Science (cum laude distinction) with a thesis called "Fuzzy Architectures for the Implementation of Expert Systems", at UPB. His main research interests are: fuzzy logic intelligent circuits, neural networks, intelligent systems, embedded systems, reconfigurable computers. He is author of more than 40 scientific papers published at prestigious conferences and journals. He is member of IEEE and Robotics Society of Romania. He was involved in many important projects with Fraunhofer Institute, Berlin, being the leader of the research groups that successfully finalized projects like „Trusted Safe" (2010) ‚E-Caesar EUSDRO" (2008),„High Performance Computing of Personalized Cardio Component Models - HEART"(2011).

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