



HAL
open science

Contrôle adaptatif backstepping de structures à base isolée hystérétiques

Francesc Pozo, Gisela Pujol, Fayçal Ikhouane, José Rodellar

► **To cite this version:**

Francesc Pozo, Gisela Pujol, Fayçal Ikhouane, José Rodellar. Contrôle adaptatif backstepping de structures à base isolée hystérétiques. 7e colloque national en calcul des structures, CSMA, May 2005, Giens, France. hal-01813017

HAL Id: hal-01813017

<https://hal.science/hal-01813017>

Submitted on 12 Jun 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Public Domain

Contrôle adaptatif backstepping de structures à base isolée hystérétiques

Francesc Pozo* — **Gisela Pujol*** — **Fayçal Ikhouane ****— **José Rodellar****

* *Escola Universitària d'Enginyeria Tècnica Industrial de Barcelona
Universitat Politècnica de Catalunya
Comte d'Urgell, 187. 08036 Barcelona, Espagne.
{francesc.pozo, gisela.pujol}@upc.edu*

** *Departament de Matemàtica Aplicada III
Universitat Politècnica de Catalunya
Jordi Girona, 1-3. 08034 Barcelona, Espagne.
{faycal.ikhouane, jose.rodellar}@upc.edu*

RÉSUMÉ. On considère un système hybride de contrôle sismique pour des structures ou bâtiments. Ce système hybride combine un isolement de base non linéaire et passif avec un système de contrôle actif. L'objectif du système actif appliqué à la base de la structure est maintenir le déplacement de la base relatif au sol et le déplacement relatif des étages de la structure dans un intervalle raisonnable en fonction du dessin de l'isolement de base. Cet isolement de base présente un comportement hystérétique qui peut être décrit analytiquement grâce au modèle de Bouc-Wen. Le modèle analytique de ce système peut se représenter de deux manières différentes: en coordonnées absolues (en relation à un axe d'inertie) ou en coordonnées relatives au sol. On présente une comparaison entre les deux stratégies et des simulations numériques.

ABSTRACT. A hybrid seismic control system for building structures is considered, which combines a class of passive nonlinear base isolator with an active control system. The objective of the active control component applied to the structural base is to keep the base displacement relative to the ground and the interstory drift within a reasonable range according to the design of the base isolator. The base isolator device exhibits a hysteretic nonlinear behavior which is described analytically by the Bouc-Wen model. The control problem is formulated representing the system dynamics in two alternative coordinates: absolute (with respect to an inertial frame) and relative to the ground. A comparison between both strategies is presented by means of numerical simulations.

MOTS-CLÉS : contrôle hybride, isolement de base, backstepping, modèle de Bouc-Wen.

KEYWORDS: hybrid control, base isolation, adaptive backstepping, Bouc-Wen model.

1. Introduction

With the aim of keeping the seismic response of structures within safety, service and comfort limits, the idea of combining both passive base isolators and feedback controllers has been increasingly considered in the last years. Some works have proposed active feedback systems, like (Kelly *et al.*, 1987), (Barbar *et al.*, 1995) and (Irschik *et al.*, 1998). More recently, semiactive controllers have been proposed in the same setting trying to get advantages of their easier implementation (see for instance (Luo *et al.*, 2001) and (Ramallo *et al.*, 2002)).

The basic concept of base isolation is to ideally make the structure behave like a rigid body through a certain degree of decoupling from the ground motion. In this way it is possible to absorb part of the energy induced by the earthquake, by reducing simultaneously the relative displacements of the structure with respect to the base and the absolute accelerations. The feasibility of adding a feedback control is based on the premise that only a control action is to be applied at the base and with force magnitudes which are not excessive due to the high flexibility of the isolators. The benefits of the inclusion of the control lie mainly in that the “cooperation” of such a force can avoid large displacements of the base isolator, which could endanger the scheme integrity; and it may also introduce an additional resistant scheme not dependable of the interstory drifts, which are already small due to the effect of the isolator. This may be useful, for instance, for buildings having particularly sensitive installations.

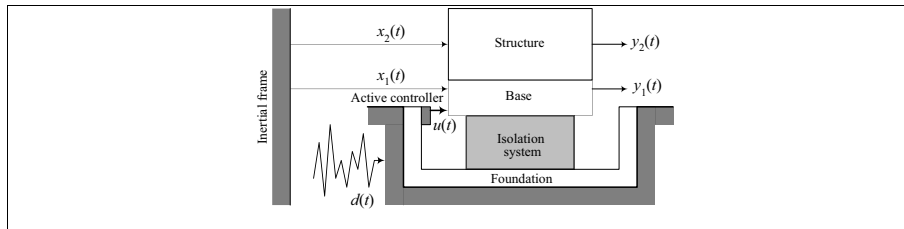


Figure 1. *Building structure with hybrid control system.*

The development of a control law to calculate the active forces involves difficulties associated with the nonlinear behavior of the base isolators and with the uncertainties in the models. An important issue in the control formulation is the coordinates adopted to represent the motion. Some authors have used models based on coordinates relative to the ground for the control design (see for example (Irschik *et al.*, 1998) and (Ramallo *et al.*, 2002)). Other authors have approached the problem by using absolute coordinates with respect to an inertial frame of reference, like in (Barbar *et al.*, 1995), (Kelly *et al.*, 1987) and (Luo *et al.*, 2001).

In this paper, we design a control system for a base isolated structure by using models in both coordinates to consider their advantages and drawbacks.

2. Structural models

Consider a base isolated structure with an active controller as illustrated in Figure 1. The passive component consists of a hysteretic base isolator. The whole system can be described by a model composed of two coupled systems: Σ_s (the structure) and Σ_b (the base). It can be represented in two different coordinate systems: absolute (with respect to an inertial frame) and relative to the ground. The relative equations of motion are

$$\Sigma_b^r : m_1 \ddot{y}_1 + (c_1 + c_2) \dot{y}_1 + (k_1 + k_2) y_1 = k_2 y_2 + c_2 \dot{y}_2 - \Phi(y_1, t) - m_1 \ddot{d} + u \quad [1]$$

$$\Sigma_s^r : m_2 \ddot{y}_2 + c_2 \dot{y}_2 + k_2 y_2 = k_2 y_1 + c_2 \dot{y}_1 - m_2 \ddot{d} \quad [2]$$

The absolute equations of motion are the following:

$$\Sigma_b^a : m_1 \ddot{x}_1 + (c_1 + c_2) \dot{x}_1 + (k_1 + k_2) x_1 = k_2 x_2 + c_2 \dot{x}_2 - \Phi(x_1 - d, t) - c_1 \dot{d} + k_1 d + u \quad [3]$$

$$\Sigma_s^a : m_2 \ddot{x}_2 + c_2 \dot{x}_2 + k_2 x_2 = k_2 x_1 + c_2 \dot{x}_1 \quad [4]$$

where m_1 and m_2 are the mass of the base and the structure, respectively; c_1 and c_2 are the damping coefficients; k_1 and k_2 are the stiffness coefficients; the absolute displacement of the base is x_1 and the absolute displacement of the structure is x_2 ; the dynamic earthquake excitation is produced by a horizontal seismic ground motion characterized by a displacement $d(t)$ with corresponding velocity and acceleration; the base displacement relative to the ground is $y_1 = x_1 - d$ while $y_2 = x_2 - d$ is the relative structure displacement; and Φ is the restoring force characterizing the hysteretic behavior of the isolator material, which is usually made with inelastic rubber bearings.

The hysteretic force Φ is described by the Bouc-Wen model (Wen, 1976) in the following form:

$$\Phi(x, t) = \alpha k_0 z(t) + (1 - \alpha) D k_0 z(t) \quad [5]$$

$$\dot{x} = D^{-1} [A \dot{x} - \beta |\dot{x}| |z|^{n-1} z - \gamma \dot{x} |z|^n] \quad [6]$$

where $\Phi(x, t)$ can be considered as the superposition of an elastic component and a hysteretic component. The hysteretic part involves a dimensionless auxiliary variable z which is the solution of the nonlinear first order differential equation [6]. In this equation, A, β and γ are dimensionless parameters which control the shape and the size of the hysteresis loop, while n governs the smoothness of the transition from elastic to plastic response.

3. Control strategies

Looking at equation [1], it is clear that a feedback control law can be designed to supply a force u able to control the relative displacement of the base against the earthquake excitation, which is the ground acceleration. However, this excitation

enters also in equation [2], which has no control. This means that the relative motion of the structure is subjected to the seismic acceleration but no feedback control is directly exerted to mitigate the effect of this excitation. In fact, the use of relative coordinates arises from the desire to keep the motion (displacement and velocity) of each floor relative to the ground small (and hence, of a given floor relative to those below and above it). Roughly speaking, feedback control is employed to achieve that end attempting “to move the whole structure” so as to follow the motion of the ground (Kelly *et al.*, 1987).

Looking at equation [3], it is clear that a feedback control law can be designed to supply a force u able to control the absolute displacement of the base against the earthquake excitation, which is now a linear combination of the ground displacement and velocity. We may observe that this excitation does not enter in equation [4]. Then, the control of the base motion leads to the control of the structure's motion. Also, it is expectable that the effort to control the system [3]-[4] be smoother than in the case of controlling system [1]-[2] since the ground displacement and velocity are smoother than the ground acceleration. The origin of the use of absolute coordinates can be found in (Kelly *et al.*, 1987) based on the idea of keeping the whole structure stationary relative to its initial configuration (i.e., relative to an inertial frame of reference) and, roughly speaking, “letting the ground move under it”.

In order to establish a comparison between both alternatives we consider: (a) measure y_1 and regulate y_1 (relative coord.); (b) measure x_1 and regulate x_1 (absolute coord.). In Section 5, a comparison between the strategies is presented.

4. Controller design

For the control design, the models [1]-[2] and [3]-[4], respectively, along with equations [5]-[6], can be written in the form

$$y_1(t) = [B(s)/A(s)]u(t) + p_r(t) \quad [7]$$

$$x_1(t) = [B(s)/A(s)]u(t) + p_a(t) \quad [8]$$

where, in order to simplify the notation, the explicit expressions of the transfer functions have been omitted. The signals $p_r(t)$ and $p_a(t)$ include all disturbances due to the hysteretic model and the earthquake excitation.

In a previous work (Ikhouane *et al.*, 2004) it has been shown that the hysteretic component in equation [5] resulting from equation [6] is always bounded for any displacement $x(t)$. This allows to consider the hysteretic component as a bounded disturbance and therefore $p_r(t)$ and $p_a(t)$ includes now all bounded disturbances due to the hysteretic model and the earthquake excitation.

We have also considered that the parameters of the models are uncertain. For that reason, we use adaptive control to stabilize the closed loop. The adaptive

control law and the parameter update laws are designed in 2 steps and it can be easily shown that all the signals of the closed loop are globally bounded (Ikhouane *et al.*, 1997).

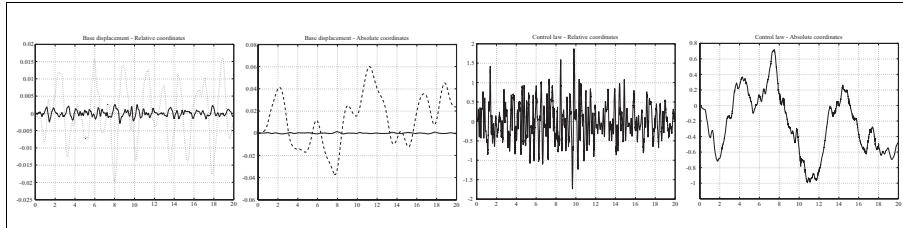


Figure 2. 1952 Taft earthquake. From left to right: closed loop base displacement (solid) and open loop base displacement (dashed) in relative and absolute coord.; control signal acceleration (m/s^2) in relative and absolute coord.

5. Numerical simulations

In our simulation, the structure is modeled as a single-degree-of-freedom system. The hysteretic parameters are $\alpha=0.5$, $k_0=61224$ N/m, $D=0.0245$, $A=1$, $\beta=0.5$ and $\gamma=0.5$. We consider the 1952 Taft and the 1989 Loma Prieta earthquakes.

A first observation of Figure 2 is that the displacements are significantly reduced both in the case of relative and absolute coordinates. Nevertheless, the interstory drift in the relative case is larger than in the passive scheme.

We can derive from the Laplace transform of the dynamical equations [2] and [4] that any improvement in the absolute base displacement x_1 leads to a direct improvement of the absolute structure displacement x_2 . Nevertheless, the improvement in the relative base displacement y_1 does not imply necessarily any improvement in the relative structure displacement, due to the perturbation earthquake term which is not zero during the ground motion.

On one hand and recalling equation [1], the control signal u has to counteract the earthquake excitation which is in the form of ground acceleration. On the other hand, the control signal in equation [3] is needed to overcome only the forces generated by ground displacement and velocity. Then, the control effort in the relative case is larger than in the absolute case, and the control signal in the absolute case is smoother than in the relative case, as can be seen in Figure 2.

6. Conclusions

From a structural engineering point of view, the objective of an active control component, as part of a hybrid seismic control system, is to keep the base displacement relative to the ground and the interstory drift within a reasonable range. This paper has proposed a backstepping adaptive control formulated using two alternative coordinates to describe the motion: relative to the ground and relative to an inertial frame. To analyze the efficiency of both approaches we have considered: (i) the base displacement relative to the ground, (ii) the interstory drift, and (iii) the control effort and the smoothness of the control signal. It has been observed that: (a) the base displacement y_1 in the relative case is clearly reduced with respect to the purely passive control whereas in the absolute case this displacement x_1-d is augmented, but it is still within an acceptable range; (b) the interstory drift in the absolute case is significantly reduced whereas in the relative case it is augmented with respect to the passive situation. Anyhow, both displacements can be considered acceptable; (c) the control signal in the absolute case is relatively smooth. The control signal in the relative case contains high-frequencies. The control effort is larger in the relative coordinate strategy. Taking into account the previous considerations, one can conclude that the use of the absolute coordinates strategy is recommended.

7. Bibliographie

- Barbat A., Rodellar J., Ryan E., Molinares N., «Active control of nonlinear base-isolated buildings», *Journal of Engineering Mechanics*, vol. 121, n° 6, 1995, p. 676.
- Ikhouane F., Rabeh A., Giri F., «Transient performance analysis in robust nonlinear adaptive control», *Systems and Control Letters*, vol. 31, 1997, p. 21.
- Ikhouane F., Mañosa V., Rodellar J., «Bounded and dissipative solutions of the Bouc-Wen model for hysteretic structural systems», *Proceedings of the ACC*, 2004.
- Irschik H., Schlachter K., Kugi A., «Control of earthquake excited nonlinear structures using Lyapunov's theory», *Computers and Structures*, vol. 67, 1998, p. 83.
- Kelly J., Leitmann G., Soldatos A., «Robust control of base-isolated structures under earthquake excitation», *J. of Optimization Theory and Appl.*, vol. 53, n° 2, 1987, p. 159.
- Luo N., Rodellar J., Vehí J., De la Sen M., «Composite semiactive control of a class of seismically excited structures», *J. of the Franklin Institute*, vol. 338, 2001, p. 225.
- Ramallo J., Johnson E., Spencer B., «Smart base isolation systems», *Journal of Engineering Mechanics ASCE*, vol. 128, n° 10, 2002, p. 1088.
- Wen Y., «Method of random vibration of hysteretic systems», *Journal of Engineering Mechanics ASCE*, vol. 102, n° 2, 1976, p. 249.