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# Slope constraint of accumulated number of switching for the control of semi-active control system

JaeSang Shin, JinWook Joung and Lan Chung
*Dankook University, Gyeonggi-do, Republic of Korea*

ABSTRACT: This paper presents the newly proposed engagement-disengagement conditions which are specially designed to decrease the amount of switching by constraining the slope of accumulated number of switching over time for the active interaction control (AIC) system. The AIC system was proposed to reduce the primary structural responses by active controlled switching between the status of the engagement (i.e., primary structure and auxiliary structure are engaged) and disengagement (i.e., primary structure and auxiliary structure are disengaged) through the interaction device. Previously proposed algorithms regulating the switching at each discrete time instants were shown to be effective in reducing the structural responses, but have the main drawback of increasing the amount of switching excessively due to the use of densely spaced discrete time instants. The steep slope of accumulated number of switching over time represents the rapid increase in the amount of switching. To constrain the slope of accumulated number of switching effectively, the regions where the switching is activated or deactivated are separated intentionally by considering the information of the current status (i.e., engagement or disengagement) in the switching controller explicitly. The newly proposed algorithms are shown to be effective in restricting ineffective switching by constraining the slope of accumulated number of switching for a single degree of freedom (SDOF) system under free vibration.

## 1 INTRODUCTION

In recent years, various kinds of structural control devices have been developed to protect structures against hazards such as earthquakes and winds. Generally, they can be classified into passive, active, semi-active and hybrid control system depending on their control strategies. Among them, recently proposed semi-active control systems combine the best features of passive and active control systems and, thus, offer inherent stability and adaptability for different dynamic loading conditions (Soong & Spencer 2002, Spencer & Nagarajaiah 2003). Previously, active interaction control (AIC) system was proposed as a viable semi-active control system (Hayen & Iwan 1994, Iwan & Wang 1996).

The main objective of the AIC system is to reduce the primary structural responses by active controlled switching between the status of the engagement and disengagement through the interaction device. The interaction device enables the primary structure (PS) to be engaged or disengaged with the auxiliary structure (AS). To regulate the switching effectively, various switching control algorithms consisting of appropriately designed engagement-disengagement conditions have been developed and they were shown to be effective in reducing the structural responses of the AIC system. The recently developed tuned interaction damping (TID) system was shown to outperform the previously developed active interface damping (AID) algorithm in reducing amplified auxiliary structural responses with the use of an additional damping device installed between the AS and ground (Zhang & Iwan 2002). However, both have the main drawback of increasing the amount of switching excessively due to the use of a small control sampling period, which is necessary to ensure the control performance of the system. The excessive amount of switching can shorten the life cycle of the interaction device as well as the AS.

The excessive amount of switching results from the steep slope of accumulated number of switching over time. Therefore, the switching control algorithm designed to constrain the slope of accumulated number of switching at each discrete time instants can decrease the total amount of switching. To constrain the slope of accumulated number of switching effectively, the regions where the switching is activated or deactivated are separated intentionally by considering the information of the current status (i.e., engagement or disengagement) in the switching controller explicitly. Within those regions, the newly proposed switching control algorithms are designed to select the activated switching regions and deactivated switching regions exclusively. The previously proposed switching control algorithms have their difficulty in selecting the deactivated switching regions since they were only designed to select the activated switching regions but the deactivated switching regions were embedded implicitly. The effectiveness of the newly proposed algorithms, which are designed to restrict ineffective switching by constraining the slope of accumulated number of switching, is investigated for a single degree of freedom (SDOF) system under free vibration.

## 2 AIC (ACTIVE INTERACTION CONTROL) SYSTEM

The AIC system consists of the PS, the AS, and the interaction device. Generally, the AS is designed to have high stiffness and low mass compared to the PS. The interaction device acts as an on-off locking device enabling the PS and AS to be engaged or disengaged.

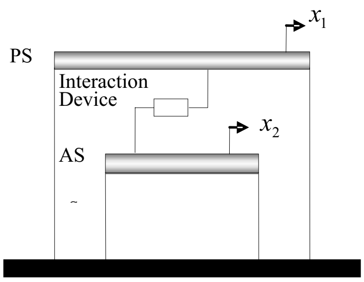


Figure 1. AIC system

The mathematical model for the AIC system with pure on/off locking device can be described as follows (Zhang & Iwan 2002). Consider the PS and AS are subjected to earthquake ground motion $\ddot{x}_g$. The equations of motion of the PS and AS are given by

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -m_1\ddot{x}_g - u_q(t)$$
$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 = -m_2\ddot{x}_g + u_q(t) \quad (1)$$

where,

$$u_{ON}(t) = \frac{m_1k_2x_2(t) - m_2k_1x_1(t)}{m_1+m_2} + \frac{m_1c_2 - m_2c_1}{m_1+m_2}\dot{x}_1(t)$$

$$u_{OFF}(t) = 0$$

in which $x_1$ and $x_2$ are the displacements of the PS and AS relative to the ground, respectively, and $m_1, c_1, k_1$ and $m_2, c_2, k_2$ are the mass, damping, and stiffness of the PS and AS, respectively. $u_q(t)$ is the interaction force applied to the PS and AS under each particular mode of operation, *ON* and *OFF*.

The terms *ON* and *OFF* represent the modes of operation engagement and disengagement, respectively. During the mode *ON,* the interaction force (e.g., $u_{ON}(t)$) is developed between the PS and AS due to the rigid connection. During the mode *OFF*, they are in the state of free movement, thus no interaction force (e.g., $u_{OFF}(t)$) is developed between them. The interaction forces acting on the PS and AS are equal in magnitude and opposite in direction. The controlled switching between *ON* and *OFF* is regulated by the switching signal $q(t) \in \{ON,\ OFF\}$ generated from the switching controller. It is assumed here that an IE can react instantaneously to the switching signal.

## 3 AID (ACTIVE INTERFACE DAMPING) ALGORITHM

The global behavior of the AIC system consists of four partitioned regions; *ON* to *OFF*, *OFF* to *ON*, *OFF* to *ON*, and *OFF* to *OFF*. The engagement and disengagement conditions of the AID algorithm were originally developed to activate the switching from the mode *OFF* and *ON*, respectively. The switching is activated or deactivated at each discrete time instant, which is evenly spaced discrete instant defined by the control sampling period $T = t_{k+1} - t_k$ (Zhang & Iwan 2002). However, the engagement and disengagement conditions implicitly deactivate the switching from the mode *ON* and *OFF*, respectively. Therefore, the engagement condition makes two partitioned regions (e.g., *OFF* to *ON* and *ON* to *ON*) overlap and the disengagement condition makes two partitioned regions (e.g., *OFF* to *OFF* and *ON* to *OFF*) overlap.

Unlike the previously developed AID algorithm, considering the information of the current status (i.e., engagement or disengagement) in the switching controller enables us to select four partitioned regions explicitly; the information of the current status can prevent each partitioned regions from overlapping. The four partitioned regions are referred here as two activated switching regions (e.g., *ON* to *OFF* and *OFF* to *ON*) and two deactivated switching regions (e.g., *ON* to *ON* and *OFF* to *OFF*), respectively.

Furthermore, how the engagement and disengagement conditions of the AID algorithm select each mode can be fully described by using the information of the current status in the switching controller. Table 1 represents each condition defining each region for the AID algorithm. The AID algorithm uses measured system information of the PS and AS to decide whether they are engaged or disengaged at each discrete time instant $t = kT$.

Table 1. AID algorithm considering current status

| Switching decision | Switching condition |
|---|---|
| $q(t) = ON$ | |
| Disengagement activated | $u(kT)\cdot\dot{x}_1(kT) < 0$ |
| Disengagement deactivated | The complement of the disengagement condition |
| $q(t) = OFF$ | |
| Engagement activated | $u(kT)\cdot\dot{x}_1(kT) \ge 0$ |
| Engagement deactivated | The complement of the engagement condition |

## 4 NSC (NONLINEAR SLOPE CONSTRAINT) ALGORITHM

New switching control algorithms are proposed here to reduce excessive amount of switching induced by the AID algorithm by constraining the slope of accumulated number of switching effectively. Additional conditions are added to the AID algorithm to eliminate the redundant switching triggered from the previously developed AID algorithm. Table 2 represents each condition defining each region for the NSC algorithm. The slope of accumulated number of switching $S_{kT}$ at time $t = kT$ is defined by the accumulated number of switching at time $t = kT$ divided by time $t = kT$. The parameters $\lambda$ and $\tau$ represent predetermined slope of accumulated number of switching and the specific time instant when the AIC system is forced to dwell on the mode *OFF*.

Table 2. NSC algorithm considering current status

| Switching decision | Switching condition |
|---|---|
| $q(t) = ON$ | |
| Disengagement activated | $u(kT)\cdot \dot{x}_1(kT) < 0 \cap S_{kT} \le \lambda$ |
| Disengagement deactivated | The complement of the disengagement condition |
| $q(t) = OFF$ | |
| Engagement activated | $u(kT)\cdot \dot{x}_1(kT) \ge 0 \cap$ $S_{kT} \le \lambda \cdot (kT \le \tau)$ |
| Engagement deactivated | The complement of the engagement condition |

## 5 NUMERICAL SIMULATION

To check the effectiveness of the NSC algorithm over the AID algorithm, numerical simulation is performed for free vibration. Free vibration simulation offers deep insight into the AID and NSC algorithms since the switching decision is not disturbed by undesirable external disturbances such as earthquakes and noises. The natural period and damping ratio of the PS are set to $1\sec$ and $2\%$. The mass of the PS is nondimensional unity; $m_1 = 1kg$. The dynamics of the AS is determined by the following parameters (Zhang & Iwan 2002).

$$\alpha = \frac{k_2}{k_1} \qquad \psi = \frac{\omega_2}{\omega_1} \qquad \gamma = \frac{\zeta_2}{\zeta_1} \tag{2}$$

The values for $\alpha$ $\psi$ and $\gamma$ are set to 2, 20 and 1, respectively (Zhang & Iwan 2002). The units for the stiffness and the damping are $N/m$ and $N\cdot\sec/m$, respectively. Initial conditions for the PS and the AS are set to $x_{10} = 1\ cm$, $x_{20} = 0$ and $\dot{x}_{10} = \dot{x}_{20} = 0$. A sufficiently small control sampling period 0.004s is used to guarantee the desirable control performance of the AIC system.

The AID algorithm is shown to guarantee the desirable control performance of the AIC system. Figure 2 shows the displacement of the PS and corresponding accumulated number of switching over time. It can be seen that the displacements of the PS converges satisfactorily to zero equilibrium point in a finite time 3s approximately. However, the switching between *ON* and *OFF* still occurs after the displacement of the PS converges to the origin closely. The total amount of switching induced by the AID algorithm is 86 in 5s.

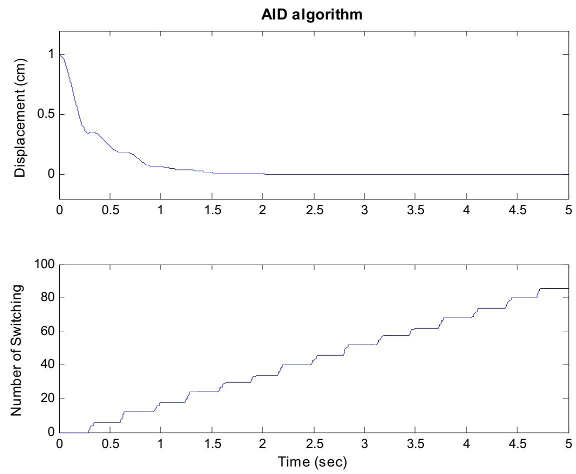


Figure 2. Displacement time history of the PS and accumulated number of switching induced by the AID algorithm

The NSC algorithm enables the AIC system to stay under the mode OFF permanently by selecting the parameter $\tau$ appropriately. The parameter $\tau$ is set to 3 since the switching occurring after 3s for the AID algorithm is unnecessary for improving the control performance of the AIC system. The redundant switching can be prevented and, thus, the total amount of switching can be reduced significantly in a given time frame. The parameter $\lambda$ defines the value of slope to be constrained. The value of slope $\lambda$ is set to 10 by trial-and-error. Figure 3 shows the displacement of the PS and corresponding accumulated number of switching over time. The total amount of switching induced by the NSC algorithm is 31. The total amount of switching is reduced by 64% over the AID algorithm due to the elimination of redundant switching after 3s.

Previously, exact measured values of state variables of the PS and AS are used for the switching controller in deciding the switching. The robustness to system perturbation such as measurement error is considered for the switching controller. Small errors due to measurement noise make the switching controller misjudge determining appropriate switching signal at each switching time. Unnecessary switching can be triggered by them and lead to the escalating number of switching, especially, for sufficiently small control sampling period due to its dense observation points.

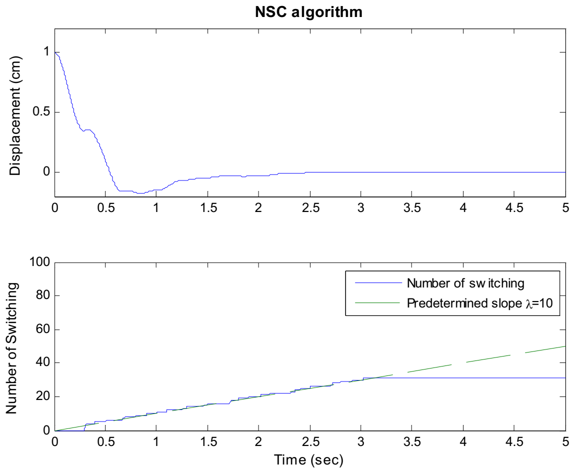


Figure 3. Displacement time history of the PS and accumulated number of switching induced by the NSC algorithm

The measurement noise is generated from the MATLAB built-in function *randn* and shown in Figure 4. The noise level is selected not to damage the control performance of the AIC system much. The measured system information is defined as follows and used for logic-based switching rules of each algorithm to determine the switching signal.

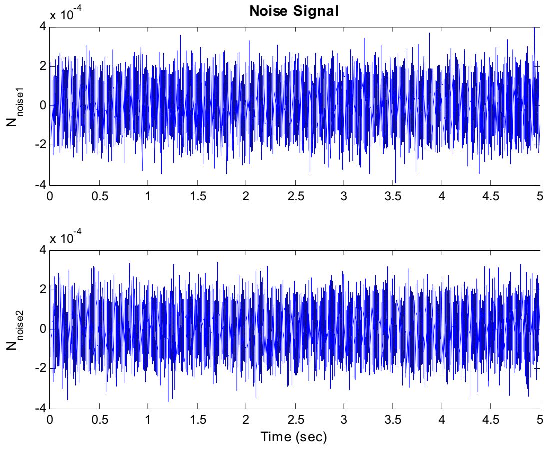


Figure 4. Measurement noise level

$$\begin{bmatrix} \hat{x}_1 \\ \hat{\dot{x}}_1 \end{bmatrix} = \begin{bmatrix} x_1 + N_{noise1} \\ \dot{x}_1 + N_{noise1} \end{bmatrix} \quad \begin{bmatrix} \hat{x}_2 \\ \hat{\dot{x}}_2 \end{bmatrix} = \begin{bmatrix} x_2 + N_{noise2} \\ \dot{x}_2 + N_{noise2} \end{bmatrix} \tag{3}$$

The same tuning parameters presented before are used for the NSC algorithm. Figure 5 shows the displacement of the PS and corresponding accumulated number of switching over time for the AID and NSC algorithms, respectively. Figure 6 shows *ON-OFF* switching signal for the AID and NSC algorithms, respectively.

The AID algorithm is highly sensitive to measurement errors as shown from Figure 5. The total amount of switching for the duration of 5s for the AID algorithm is 501, while the total amount of switching without measurement errors is 86. From Figure 5, the steep slope indicating the fast switching is observed after the displacement of the PS converges to the origin closely.

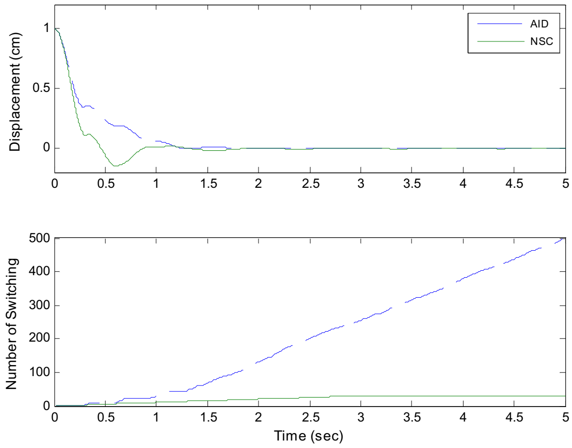


Figure 5. Displacements of the PS and accumulated number of switching induced by the AID and NSC algorithms

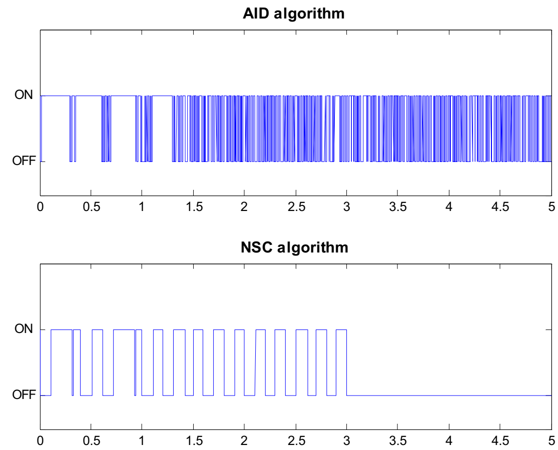


Figure 6. *ON-OFF* switching signal induced by the AID and NSC algorithms

For the NSC algorithm, the additional switching rules deciding the switching based on the information of the slope of accumulated number of switching provide the AIC system the robustness with respect to the measurement errors. The parameter $\tau$ enabling the AIC system to stay under the mode OFF permanently can attenuate the increasing number of switching triggered by the small deviation of measured information. It is clearly seen that the total amount of switching is reduced significantly from Figure 5.

## 6 CONCLUSION

The previously developed AID (Active Interface Damping) algorithm is shown to require excessive amount of switching in regulating the switching for the AIC (Active Interaction Control) system. The NSC algorithm is proposed here to restrict redundant switching triggered by the AID algorithm. It is shown to reduce the total amount of switching over the AID algorithm by constraining the slop of the accumulated number of switching. Furthermore, it is shown to be robust to measurement error and, thus, the number of switching occurring from the effect of measurement noise can be prevented effectively. In the presence of measurement noise, the total amount of switching is greatly reduced over the AID algorithm.

## 7 REFERENCES


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