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OFFLINE AND ONLINE PERFORMANCE CONTRAST OF OPTIMAL CONTROL

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Summary. Civil structures are quite vulnerable to extreme dynamic loads as well as to natural disasters. The aforementioned problem is well-known and interestingly, unavoidable as it is almost impossible to know when that type of loads or disasters are going to hit the existing structures. Due to such unpredictability, many are interested to adopt the online or real-time control and monitoring strategy instead of conventional approach. However, still offline monitoring and vibration control strategies are useful to understand the overall performance of the investigated dynamical problem as it might not be an option to go for online due to feasibility or other constrains. In order to hold a debate, herein, the controlled performance of a multi-degree-of-freedom system has investigated both adopting offline and online approaches. The linear-quadratic regulator (LQR) algorithm has been employed as the control law and it is assumed that controller will behave as an active control system. In order to understand the effect of the optimal control, the displacements and velocities at different degree-of-freedom's level have considered and compared. The outcome suggests that both approaches have advantages and disadvantages such as offline approach is quite useful to understand at the design phase of the project, while, online approach might be very effected after the construction.

1 INTRODUCTION

Vibration induced by dynamic loads is a typical problem in the area of structural engineering and mechanics that requires serious attention. Even though, many works have been done in this area but still upgraded control techniques and technologies are necessary. There are many control algorithms and technologies are already available for real-world applications but none of them are flawless. Due to the aforementioned reason it requires further studies to improve and upgrade the performance of existing alternatives as well as developing more efficient control technologies. Furthermore, it may also be an issue, how those vibration control technologies are applied e.g., online or offline. Usually, most of the vibration control applications are implemented in offline manner, meaning, the control devices are placed and let it working without doing any real-time adjustment. In contrary, in case of online control, the device may be adjusted in real-time based on the current vibration information. As in the aforementioned case, the applied control force can be estimated in real-time, as a result it might be more effective. However, it is very difficult to say which approach may be optimal at what circumstances. For instance, online or real-time control might be beneficial but it may be difficult to operate during an natural catastrophe e.g., gale, earthquake. In the prior cases, offline or semi-online (hybrid operation with battery and/or electric power supply) could be an alternative to real-time control.

In the real-world applications, there are many vibration control alternatives. Broadly, according to their functionalities, those alternatives can be separated into passive, active, hybrid, intelligent, energy-based, adaptive, and semi-active [1, 2, 3, 4, 5, 6, 7]. Every vibration control technology comes with its advantages (e.g., no power required) and disadvantages (e.g., power supply is a must). Among the available vibration control alternatives few can be mentioned, namely, tuned mass damper (TMD) [1, 8, 9], elastomeric bearing and base isolator [10], tuned liquid damper [1, 7], actuators and active bracing and tendons [2, 3], electromagnetic and magnetorheological damper [3].

It needs to be mentioned that the selection of any vibration control technology and their implementation links to many constrains such as project cost, technology, power source, etc. Hence, it is not straightforward to say which technology ones should use. In general, important projects such as bridges, power plants, may adopt online control (it obvious that it might cost more than passive control systems that can be implemented offline) due to its possible optimal performance. In such situation, as an alternative, the hybrid control systems could also be an option that might have a combination of both passive and active/semi-active systems. Regardless of the technology, there is no guarantee of the optimal performance due to the inherent complexity of the control systems as well as for related uncertainty of the exogenous inputs. Therefore, a compromise must be made that trade-off between performances and cost. In case of implementations, the performance of passive type control systems have been studied for various structures such as bridges [10], buildings [8], offshore structures [9]. Active control approach has been investigated by many and the superior performance has been reported in [2, 11, 12]. While the use of intelligent control by using soft computing is studied by [4], and, intelligent control technique has adopted for cable-supported bridges in [13]. Adaptive type control has been adapted for spacecraft [14], whereas, similar to the adaptive approach, namely, a real-time adjustable vibration control coupled with system identification is studied in [15]. Additionally, adaptive control was adapted for smart structures [16, 17], the energy-based control has been adopted for various applications, for instance, to control mechanical systems [5, 6], human-robot physical interaction [18], beam type structures [19], tensegrity type structures [20].

The real-life application of passive system is not adjustable by any means hence such device control force can't be estimated/adjusted in real-time. In other words, online control via passive control device is not possible, while, offline control is the only option. In contrary, active, hybrid and semi-active controls can be implemented online because all of them can adjust and estimate control force in real-time based on the current information [14, 15]. This makes it clear that which technology can be used for offline and online implementations.

Due to the early mentioned reasons, this study has investigated the contrast between online and offline vibration control scenarios. The offline control is represented by the code written in MATLAB, while, the online control is represented via the use of SIMULINK. The outcome confirms that both strategies may perform well depending on the situation. However, online control might be more effective than offline as online approach can estimate the required control force based on the current information.

2 PROBLEM SPECIFICATIONS

The investigations have been done by adopting a multi-storied structure coupled with an active device at the 1st floor level. The structure is modelled as lumped-mass model and the dynamical system can be expressed as by the equation of motion given in Eq. (1). It is obvious it may differ a bit with the underlying physics-based model. However, the lumped-mass model is well established and widely used in the area of structural engineering.

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = P(t) \tag{1}$$

where t is the time vector, X, $\dot{X}$ and $\ddot{X}$ are the displacement, velocity and acceleration vectors with a dimension of $(n \times 1)$, while, M, C and K are the mass, damping, and stiffness matrices with a dimension of $(n \times n)$, and P is the input excitation (depending on the situation, it can have single or multiple inputs).

After the derivation of the equation of motion, the system needs to be brought into a more compact formulation (instead of dealing with individual DOF's equations of motion) to make simulation process faster and easier. The early mentioned formulation is known as the state-space formulation, the main benefits of having state-space formulation is that it consist of two main equations only. One of those equation is called the process or system equation given by Eq. (2) and the second one is known as the observation or measurement equation described by Eq. (3). However, the measurement equation needs to be adjusted as per the designer/engineer's wish. In other words, the observation equation must be modified depending on what a designer wants to measure, whether all degree-of-freedoms (DOFs) displacements, velocities, accelerations or just few of them instead of measuring all.

$$Z_{k+1} = AZ_k + BU_k \tag{2}$$

where A and B are the system and input matrices, respectively, Z is the state vector (contains, displacements and velocities), U is the input vector (usually, contain both excitation input and control force, if any) k is the time-steps.

$$Y_k = CZ_k + DU_k \tag{3}$$

where C is the output matrix, D is the feed-forward matrix, Y is the output vector (may have all or partial channels information).

It is mentioned earlier that there is an active device as a control mechanism that requires a control law. Hence, the linear-quadratic regulator (LQR) has been adapted as the control law due to its optimal performance and uncomplicated formulation. The LQR algorithm tries to minimizing a cost function J by optimizing the performance of the controller.

$$J = \textstyle\sum_{k=0}^{N} Z_k^T Q X_k + U_k^T R U_k \tag{4}$$

where Q and R are the weight factors (typically, it requires proper tuning).

$$f_{c_k} = -K_{opt} Z_k \tag{5}$$

where f_c is the optimal control force, K_{opt} optimal gain, Z is the full-states (all displacements and velocities). The detail formulation of LQR has been avoided as it can be found in many existing literatures [2, 15]. And the optimal performance of the LQR control law is quite well-established with the proper tuned set of the weight parameters Q and R. A conceptual framework of the studied approach is depicted in Fig. 1. According to many [2, 15, 21] the weight parameters Q needs to be semi-definitive, while, R must be strictly positive definitive.

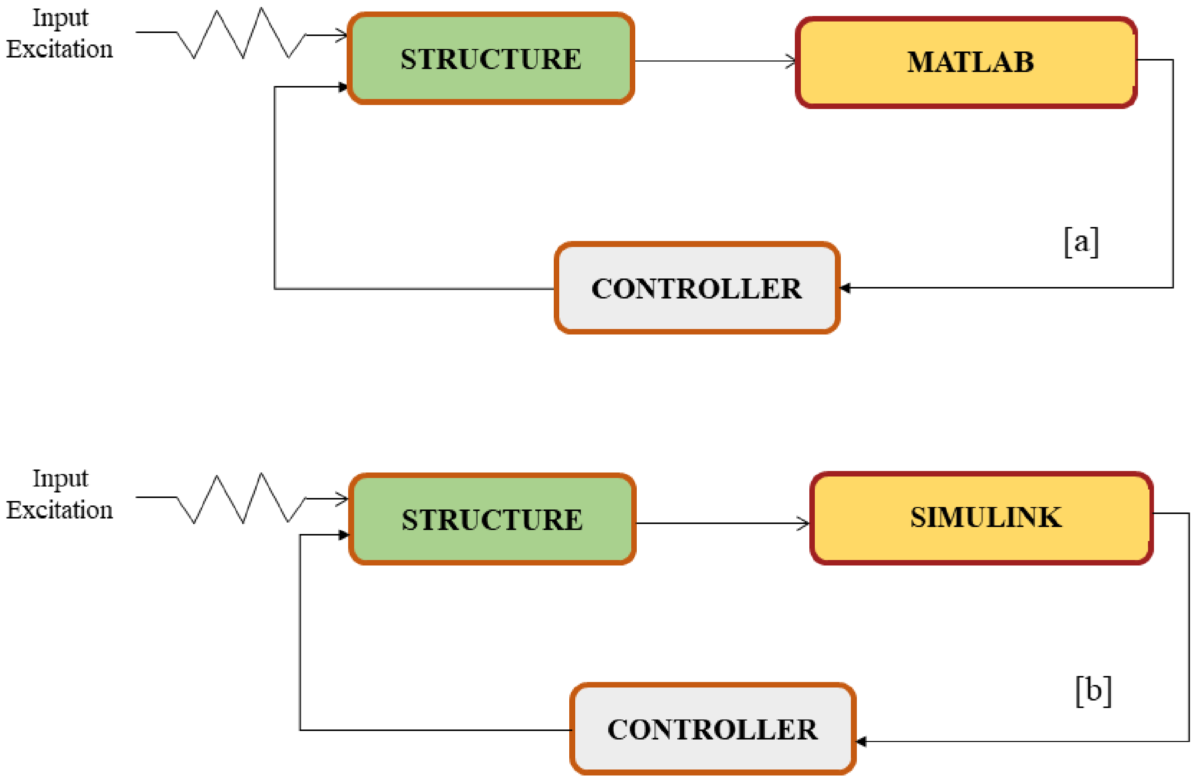

Figure 1: Conceptual framework of the implementations: (a) offline, (b) online

3 RESULTS AND DISCUSSION

The simulations are performed via the code written in MATLAB to render an offline scenario, while, the SIMULINK has been used to represent an online situation. The initialization as well as other simulations criterion for both cases remain same e.g., simulation time, sampling rate, input excitations, etc. And the input excitation force is assumed to be a complex type dynamic force as given by Eq. (6). The complex input excitation has been generated by selecting two different excitation frequencies (e.g., ω_1, ω_2). The expression of the excitation frequencies can be given as $\omega_1 = 2\pi f_1$ and $\omega_2 = 2\pi f_2$. In this study, the excitation frequencies f_1 and f_2 are selected same as the first and second resonant frequencies of the structure.

$$P(t) = \alpha Sin(\omega_1 t) + \beta Cos(\omega_2 t) \tag{6}$$

where α and β are the amplitudes of the signals respective parts, ω is the angular frequency of the excitation.

A summary of the resonant frequencies of the structure is shown in Table 1. The input excitation is presented in Fig. 1. In order to generate a realistic dynamic load the excitation force has been turned-off after half-time of the excitation. The simulations are performed with a sampling frequency of 400 Hz for a duration of 100 sec. The structure is assumed to have 7-DOFs, where, each floor weight is about 5×10^4 Kg while each floor stiffness is roughly about 7×10^7 N/m. The damping matrix is derived by using mass and stiffness of the structure. The

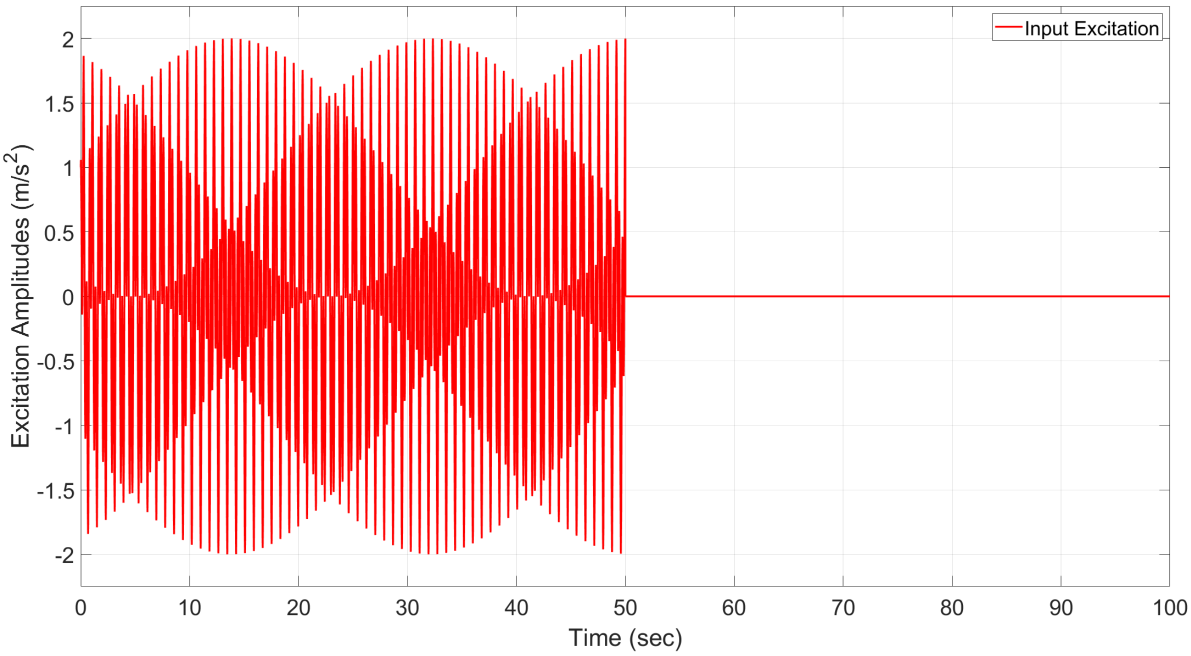

Figure 2: The input excitation

structure without any controller has been solved first, later, the controller has been coupled for both so-called "offline" and "online" cases.

Table 1: The resonant frequencies of the investigated structure

DOFs	Frequencies (Hz)
1	1.245
2	3.680
3	5.955
4	7.969
5	9.635
6	10.880
7	11.650

The response of the top DOF is compared due to the assumption that the maximum movement will occur at the top of the structure. Initially, the displacements (see Fig. 3) and velocities (see Fig. 4) of the 7th DOF has been compared for the offline controlled case with the uncontrolled response. Both of the early mentioned figures are accompanied with a zoomed sub-figure of each for better visualization. The efficacy of the controller is clearly evident from the both aforementioned figures.

Afterward, the same DOF's response (e.g., 7th) is compared by adding the results from online simulations. The displacements and velocities are depicted in Fig. 5 and Fig. 6, respectively.

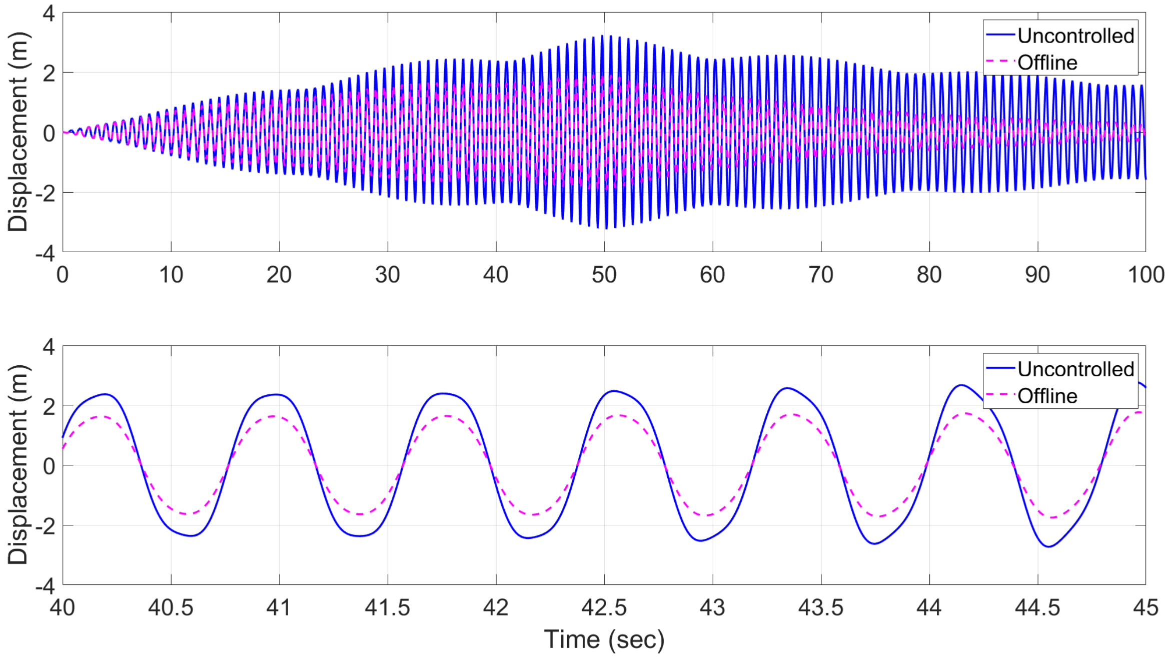

Figure 3: Comparison between the uncontrolled and offline controlled displacements of the top floor

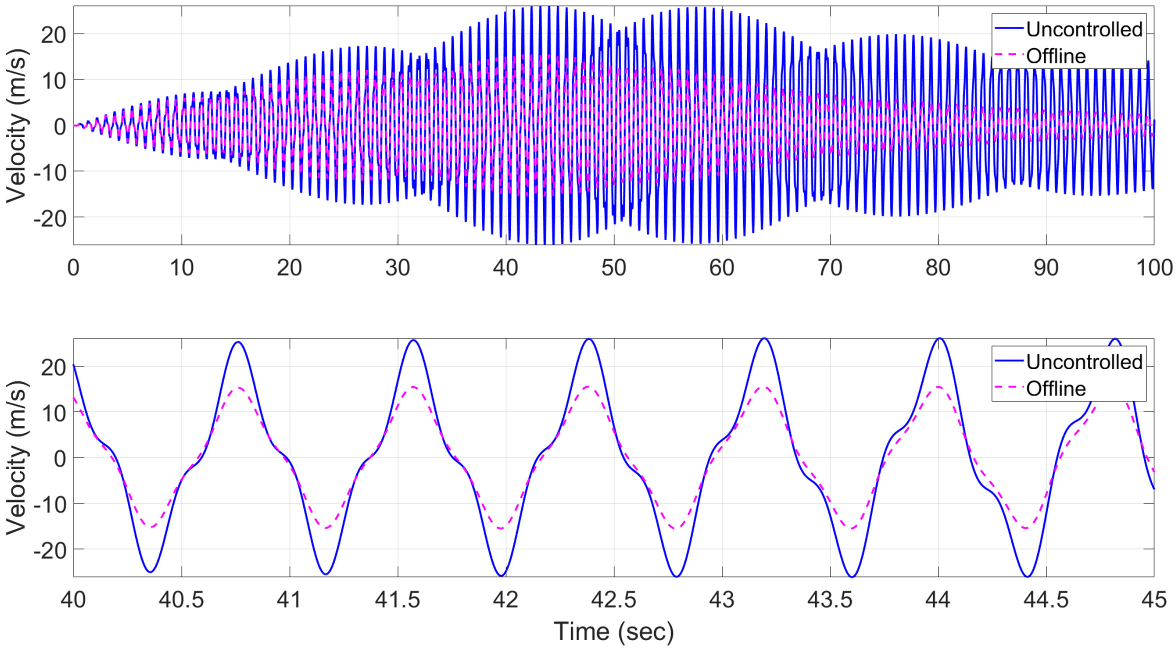

Figure 4: Comparison between the uncontrolled and offline controlled velocities of the top floor

Though the results of the "offline" and "online" cases look similar but the implementations may represents two different circumstances. For instance, the offline case may render the design phase

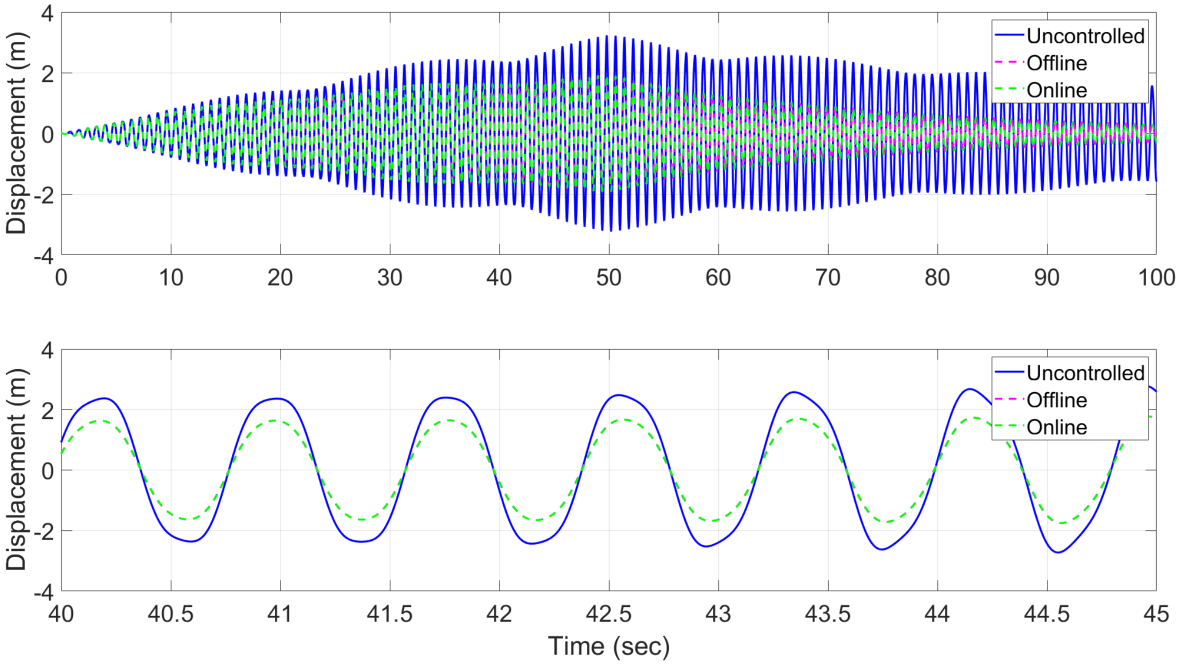

Figure 5: Comparison of the displacements of the top floor for all of the cases

or post-design phase (e.g., validation or monitoring). While the online case may represents the current situation (e.g., operational stage) as it tracks and adjust the control force in real-time or nearly real-time scenario. Hence, from the conceptual context, both approaches should yield the same results (in real-life problem due to many unknowns it may not holds). For the early mentioned reason, even though the results are alike but online case would be more realistic one. For better understanding, along with those figures, a summary of the peak minimum and maximum displacements values of all DOFs are given in Table 2.

Table 2: Summary of vibration reduction performance

DOFs	1	2	3	4	5	6	7
Uncontrolled							
Min. Peak Disp. (m)	-0.6982	-1.3180	-1.8043	-2.1469	-2.5973	-3.0095	-3.2377
Max. Peak Disp. (m)	0.6981	1.3178	1.8036	2.1471	2.5949	3.0048	3.2314
Offline Controlled							
Min. Peak Disp. (m)	-0.4152	-0.7946	-1.1118	-1.3570	-1.6069	-1.8138	-1.9254
Max. Peak Disp. (m)	0.4151	0.7943	1.1119	1.3573	1.6117	1.8211	1.9339
Online Controlled							
Min. Peak Disp. (m)	-0.4149	-0.7940	-1.1110	-1.3561	-1.6066	-1.8136	-1.9252
Max. Peak Disp. (m)	0.4148	0.7937	1.1109	1.3564	1.6115	1.8208	1.9334

Finally, a contrast of the control force versus displacement and velocity hysteresis have been

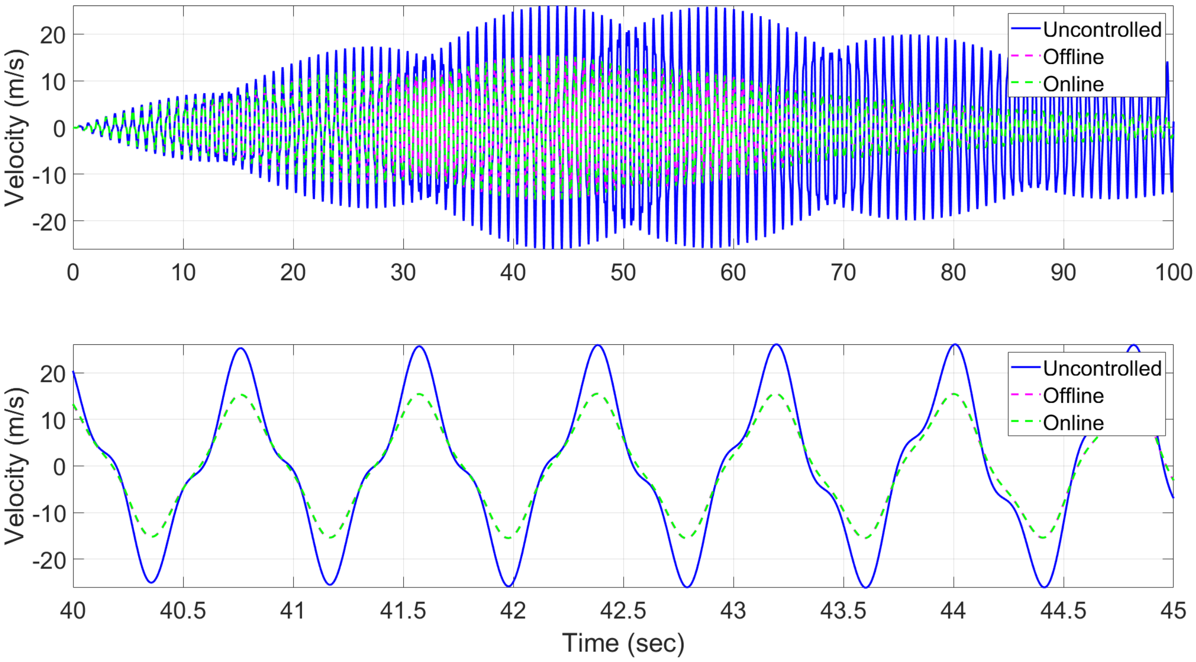

Figure 6: Comparison of the velocities of the top floor for all of the cases

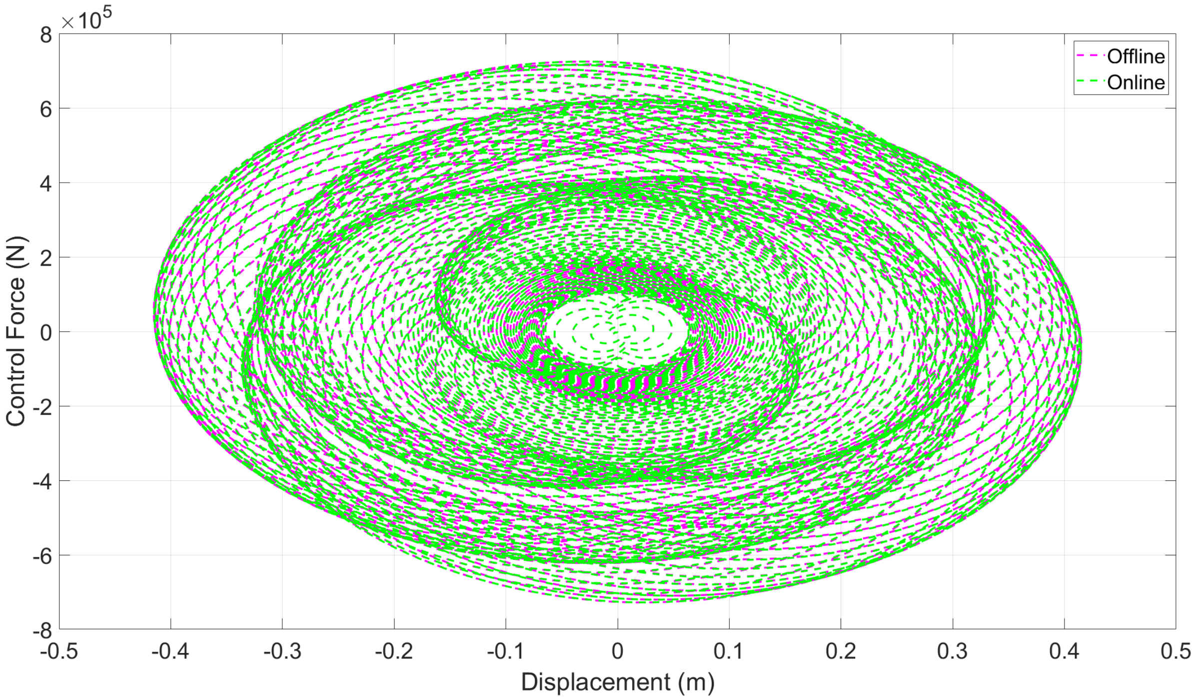

Figure 7: Hysteresis of control force and displacement

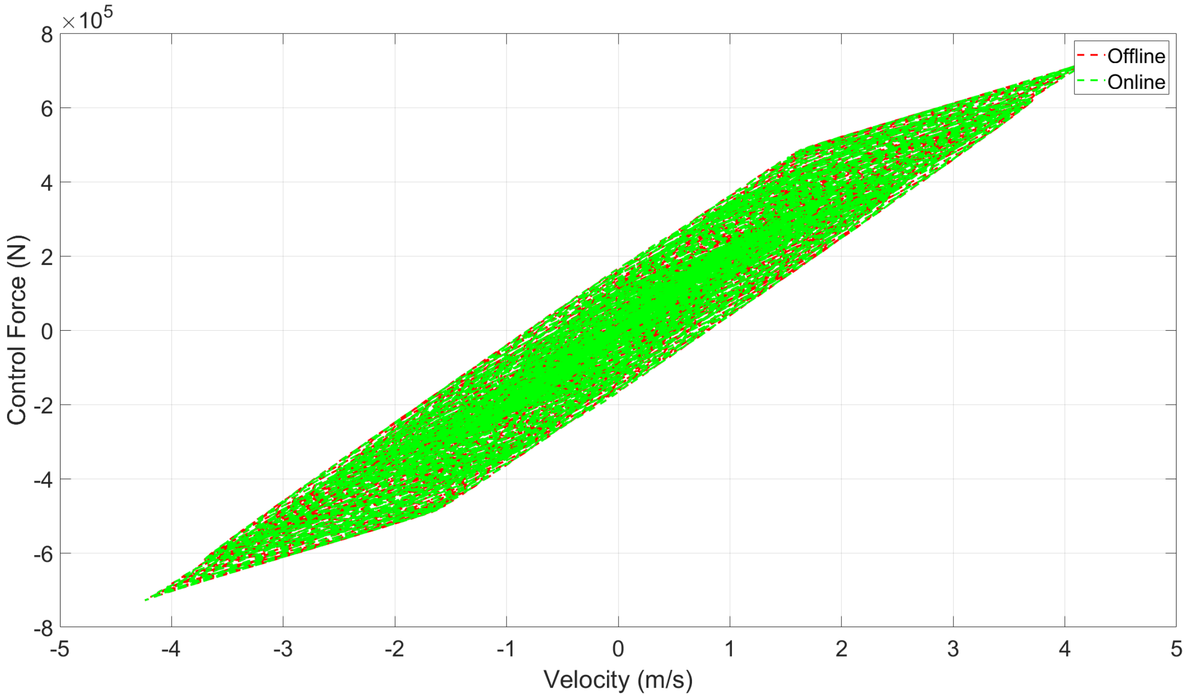

Figure 8: Hysteresis of control force and velocity

presented in Fig. 7 and Fig. 8 to understand the controller performance (e.g., stability). In short, both hysteresis confirms the implementations of the active control approach.

4 CONCLUSIONS

This study has investigated a contrast between online and offline vibration mitigation and control approaches. To do this end, a multi-storied structure is considered, where, it is assumed that a controllable active device is placed at the 1st DOF of the structure. The controlled and uncontrolled performance of the structures have been evaluated and compared. And it is observed that both “offline” and “online” cases show quite good level of reduction of vibration i.e. about 40%. Even though, the results might be pretty close for the both controlled cases but the offline case may render the design phase, whereas, the online case may tell the current situation. In a nutshell, due to the goal of optimal control the online case would be more realistic one as performance can be adjusted in real-time based on the current vibration information. However, the real-life problems are more complex due to underlying uncertainties of the nature and input excitations. Hence, further study is essential to justify the performance of the online approach by adopting tall and more complex structures excited with various input excitations.

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