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STRUCTURAL RESPONSE EVALUATION OF MULTI-STORIED FRAME USING OPTIMAL CONTROL SCHEME

Mohammad S. Miah

Assistant Professor, University of Asia Pacific, Bangladesh, e-mail: mshamim@uap-bd.edu

ABSTRACT

Vibration reduction and control of structures is a well-known problem in the area of structural engineering and mechanics. This is a branch of engineering which brings researcher from different major (i.e., mechanical, control, aerospace, and so on) in a single platform. And interestingly, all of the branches are trying to resolve the issue related to vibration mitigation and control in their respective area. In some areas such as electrical and control engineering it is quite common that they use observer such as Kalman filter for updating or predicting any missing information as they often deal with projection of trajectories. However, in order to control the vibration of any dynamical system, it is essential that the aforementioned filter is combined with a control algorithm as number of available sensors might be limited. To do this end, herein, a quite simple control algorithm so-called the viscous damping with negative stiffness (VDNS) is employed. Additionally, the VDNS scheme has been coupled with a nonlinear observer namelythe unscented Kalman filter (UKF) in order to get the possibility of adding a nonlinear system. The performance of a10-storied frame is evaluated numerically and it is observed that a significant reduction of vibration is possible via the investigated approach.

Keywords:*Vibration mitigation and control; Unscented Kalman filter; Viscous damping with negative stiffness, Dynamical system.*

1. INTRODUCTION

Dealing with dynamic loads are often a serious challenge in the area of structural vibration mitigation and control. This is a common problem in different areas of science and engineering such as aerospace engineering, mechanical engineering, physics, mechanics as well as in civil engineering. Even though several alternatives have been developed and used into the real structures still further improvement is necessary. There are various alternatives available to handle the aforementioned problem e.g. vibration mitigation. Active control (AC) is one of the best technologies among available alternatives. Typically, the implementation of the AC requires a control algorithm. Among many, the linear-quadratic regulator (LQR) is considered to be one of the best optimal control algorithm due to its simple form (Anderson and Moore 1989). However, the main drawback associated with the LQR control law is that it fully depends on full-state feedback meaning all of the floors information is necessary which is not possible due to cost effectiveness. Additionally, the selection of the weight parameters Q and R is a challenge as there is almost no proper guideline for selection of those parameters. Even though there are some guideline regarding initial starts but that doesn't help for a complicated problem reported by several researchers (Oral et al. 2010, Nekoui and Bozorgi 2011, Miah et al. 2013). Hence, it is essential to have an efficient alternative for optimal vibration mitigation. However, it needs to be mentioned that the performances may vary depending on the selection of the appropriate control law.

The use of linear Kalman filter (KF) is quite common where missing information are needed to be estimated. However, the KF is widely used for the linear system. The drawbacks of the aforementioned method are that it cannot deal with large amount of noise as well as nonlinear system (Miah 2015, Miah et al. 2017). Hence, herein a nonlinear filter is employed so-called the unscented Kalman filter (UKF). There are several advantages of using UKF such as it can handle nonlinear system quite efficiently as well as large amount of noise

(Chatzi et al. 2010, Miah 2015). Furthermore, it has the possibility to update the system states i.e., displacement and velocity and structural parameters such as stiffness (Miah et al. 2013).

There are several control laws available, broadly, they can be divided into two categories depending on their feedback; (i) full-state feedback, e.g. LQR (ii) partial feedback, e.g. viscous damping with negative stiffness (VDNS) (Dyke 1996, Preumont 2004, Miah 2015). The superior performances of VDNS control law has been verified by several researchers (Bhowmik 2011, Miah et al. 2014, Weber 2015). The aforementioned control laws have been used in different fields of science and engineering (Mobaieen et al. 2012), in particular, in the area of control, robotics, and mechanics. It needs to be mentioned that the control laws are essential not only for AC but also for semi-active control scheme as well. However, herein this study will focus on active control scheme in combination with VDNS. The efficacy of the AC has been verified by several researchers (Preumont 2004, Dyke 1996).

In this study, a 10-storied frame is considered and two dampers are assumed to be placed at the first-floor level and at top floor level. The responses are evaluated and compared with a benchmark namely uncontrolled model where no damper was used. The VDNS control law isemployed and combined with UKF to get the advantage of nonlinear problems. Also, parameters of the system along with unknown displacement and velocity can be estimated simultaneously. And the active actuator actuation principle is employed.

2. METHODOLOGY

A benchmark model of a 10-storied frame is considered where no damper is used. And in the second model there are two dampers are considered to be placed at first and top floor. The VDNS is employed and the responses are evaluated and compared. For the simplicity, it is assumed that all of the floors are having the same mass. The 10-storied dynamical system can be described via the given equation of motion,

$$M\ddot{z}(t) + C\dot{z}(t) + Kz(t) = \beta p(t) \tag{1}$$

where M, C and K indicates the mass, damping and stiffness matrices (10×10) of the system $M = \begin{bmatrix} m_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & m_{10} \end{bmatrix}$, $K = \begin{bmatrix} k_1 + k_2 & -k_2 & \cdots \\ -k_2 & \ddots & \vdots \\ \vdots & \cdots & k_{10} \end{bmatrix}$, $C = \begin{bmatrix} c_1 + c_2 & -c_2 & \cdots \\ -c_2 & \ddots & \vdots \\ \vdots & \cdots & c_{10} \end{bmatrix}$, $\ddot{z}, \dot{z}$ and z are the acceleration, velocity and displacement of the system, t is the time vector, β is a control vector that controls the input force, $p(t)$ is the input excitation.

In order to perform simulations, compact formulation is essential to make the overall simulation faster. Therefore, the state space formulation is adopted herein. There are two basic equations of state space formulation, (i) the process or system equation and (ii) measurement or observation equation. The process and observation equations are described by,

$$\begin{aligned} \dot{z}(t) &= Az(t) + Bu(t) + w(t) \\ y(t) &= Cz(t) + Du(t) + v(t) \end{aligned} \tag{2}$$

where A is the system matrix $A = \begin{bmatrix} 0_{10\times10} & I_{10\times10} \\ -(M^{-1}K)_{10\times10} & -(M^{-1}C)_{10\times10} \end{bmatrix}$ and B is the input matrix $B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & -1 \\ -m_1^{-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -m_{10}^{-1} \end{bmatrix}^T$, z is the state vector that contain displacement and velocity vector, u indicates the input force $u = [x_g \quad f_{control}]^T$, x_g is the

input excitation and $f_{control}$ represents the control force, $C$is the output matrix, D means the feedthrough matrix, w and v are the process and observation noise respectively.
The performance of the LQR control law heavily depends on the weight factors and the control force is estimated from the full-state feedback. In order to avoid the aforementioned problem, the VDNS is employed as control law due to its simplicity and another advantage is that it only require the collocated information information. However, herein non-collocated (e.g. third floor) information is used to get the best performance in terms of vibration reduction.The control law is described via the equation below,

$$f_{control}^{vdns}(t) = -k^{vdns} \times x(t) + c^{vdns} \times \dot{x}(t) \tag{4}$$

where $f_{control}^{vdns}$ is the optimal control force estimated via VDNS control law, k^{vdns} and c^{vdns} indicates the stiffness and damping coefficients of the control law accordingly, x and $\dot{x}$ are the displacement and velocity used to estimate the control force. The implemented closed-loop is depicted in Figure 1.

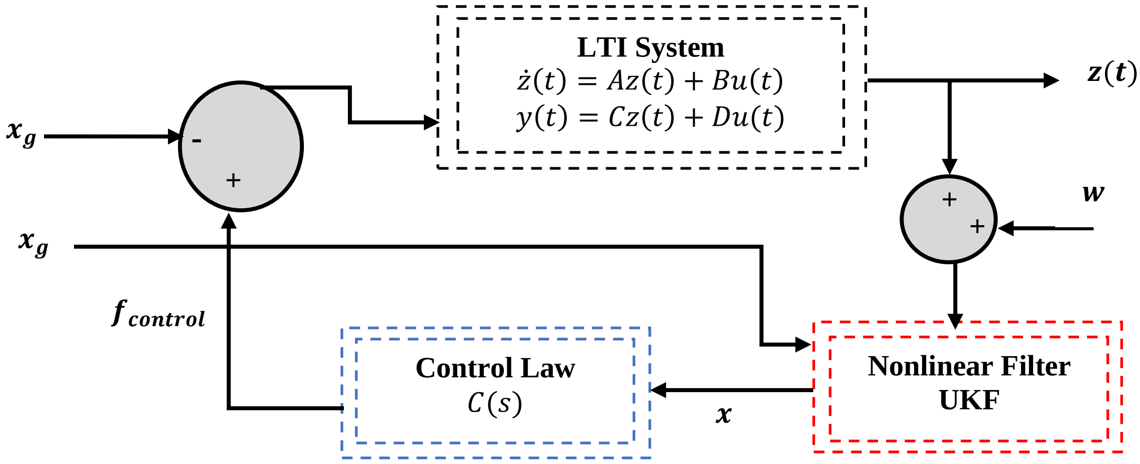

Figure 1: Closed-loop of the studied problem.

In order to perform simulations the above described closed-loop implementation is adopted. Where the *LTI System* block represents the linear time-invarient system/structure, *Nonlinear Filter UKF* block indicates the nonlinear observer and the *Control Law* block represents the implemented control scheme e.g. VDNS. It needs to be mentioned that only few floors (i.e., 1st, 5th and 10th) information e.g. accelerations are assumed to be measured.

3. NUMERICAL IMPLEMENTATIONS

The numerical simulations are done via MATLAB/SUMILINK®. The simulation is done for a sampling frequency of 500Hz and maximum time of 70sec and the load was turned off after ~46sec. A harmonic type dynamic load is employed; and the structure was excited at the first resonant frequency to observe the extreme level of vibration. The simulations are done in a nearly real-time platform so-called SIMULINK®. Firstly, a benchmark problem is evaluated to compare the responses with controlled case. The benchmark case has been named as “Uncontrolled” for simplicity. And the controlled casehas been named as “Controlled-VDNS”, represents the case with VDNS control law is combined with UKF. The responses such as displacements, velocities and acceleration are observed and compared at different floor level of the structure.

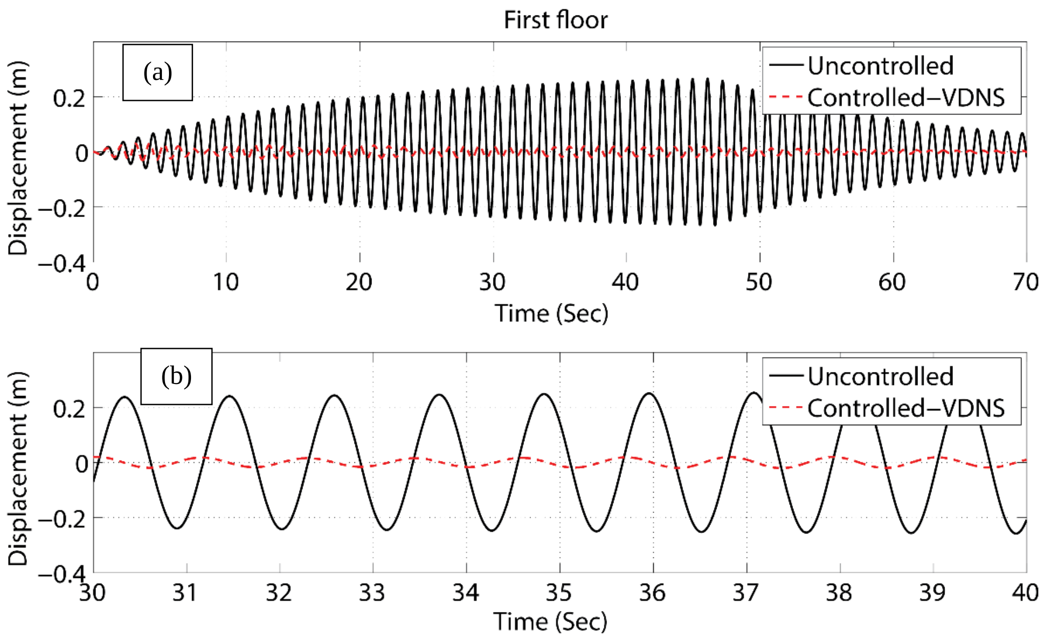

Figure 2: Comparison of the 1st floor displacement; (a) full-time history, (b) zoomed view.

In Figure 2, the comparison of the first floors' displacement trajectories are presented. In the aforementioned figure, the full time history 0-70 sec is depicted and a zoomed view from 30-40 sec is shown for the visualization purpose.

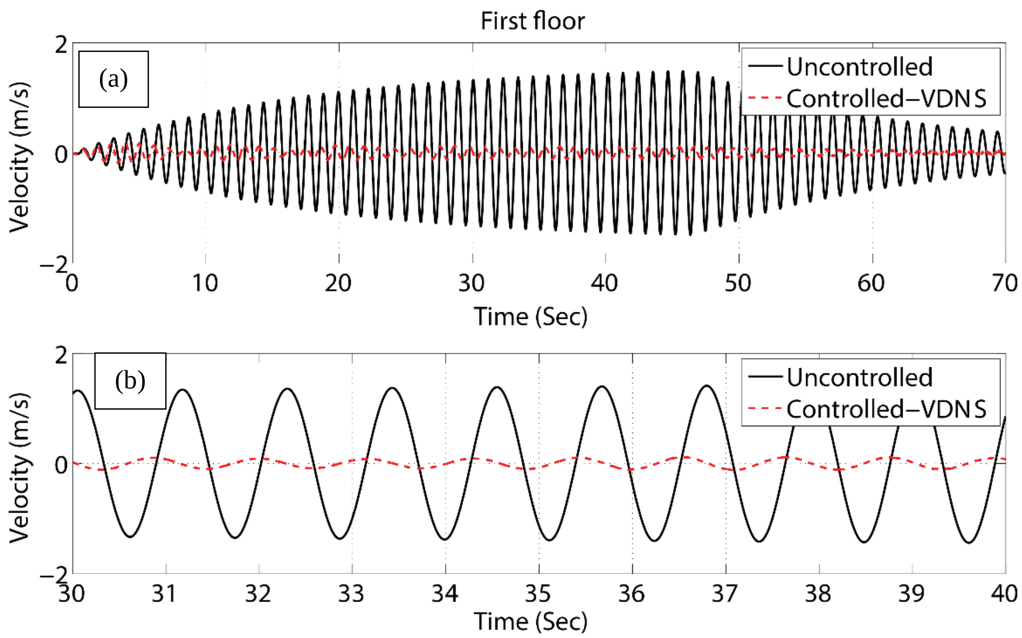

Figure 3: Comparison of the 1st floor velocity; (a) full-time history, (b) zoomed view.

The uncontrolled case in shown by black line, the dotted red line represents the VDNS control case. It can be summarized from Figure 2 that the vibration has been reduced significantly via the VDNS control approaches. It is happening due to the real-time update of the control force based on the current displacement and velocity.

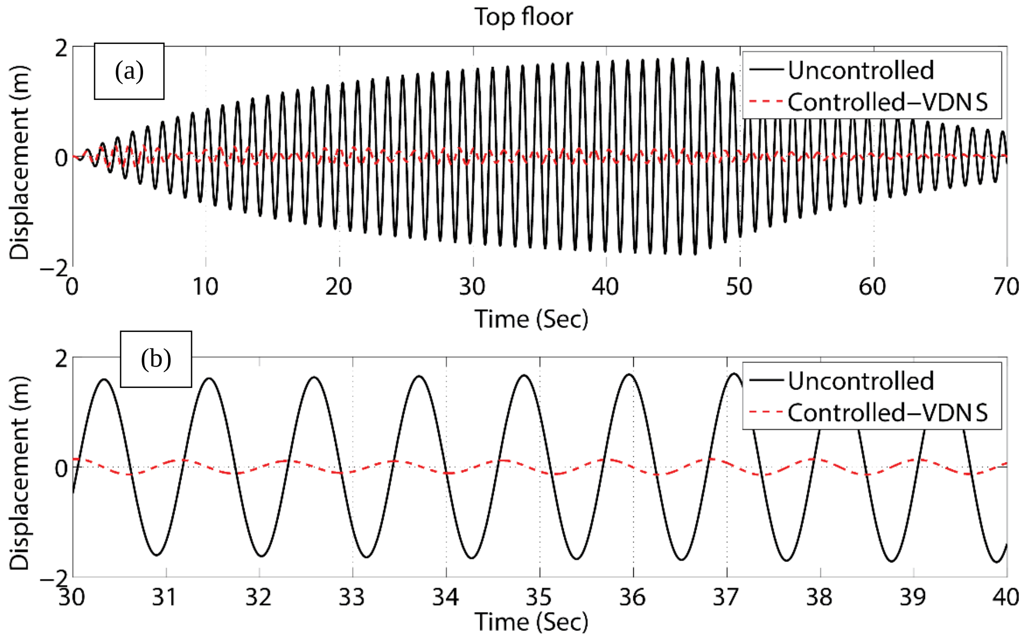

Figure 4: Comparison of the 10th floor displacement; (a) full-time history, (b) zoomed view.

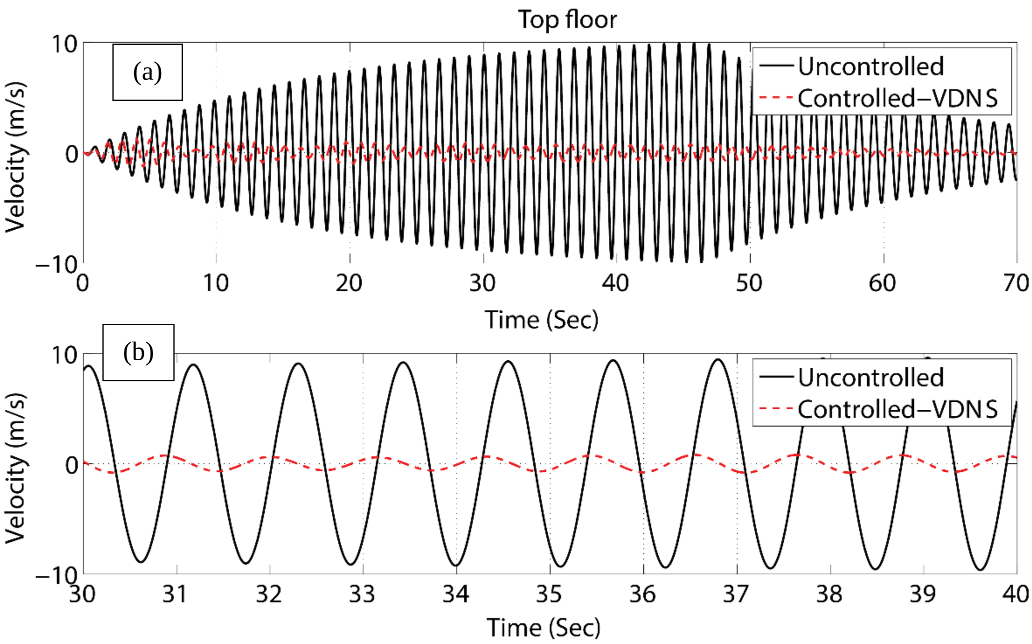

Figure 5: Comparison of the 10th floor velocity; (a) full-time history, (b) zoomed view.

Along with the aforementioned figure the velocity of the first floor is depicted in Figure 3 and quite similar results are obtained. In order to confirm the above statement, the top floor's (e.g. 10th floor) response is evaluated and presented in Figures 4-5. The color coding remain same as Figures 2 and 3. It is expected that the top floor will have more deflection which is visible in Figures 4-5. However, the reduction of the response is significant and the efficacy of the control investigated approach is observed. And most importantly, the used control scheme has the advantage over LQR as it doesnot require full-state feedback.

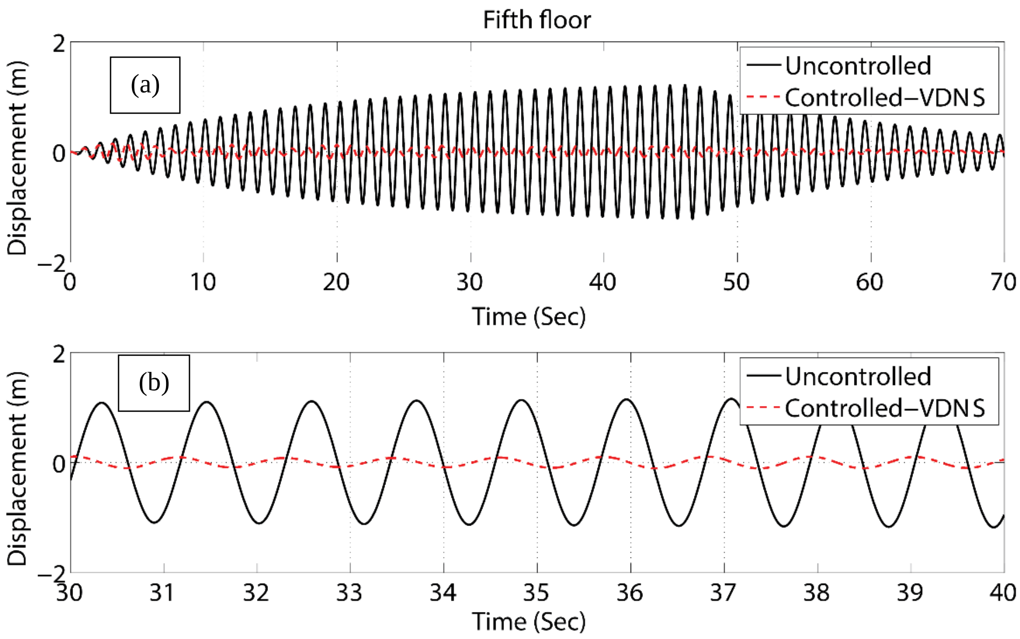

Figure 6: Comparison of the 5th floor displacement; (a) full-time history, (b) zoomed view.

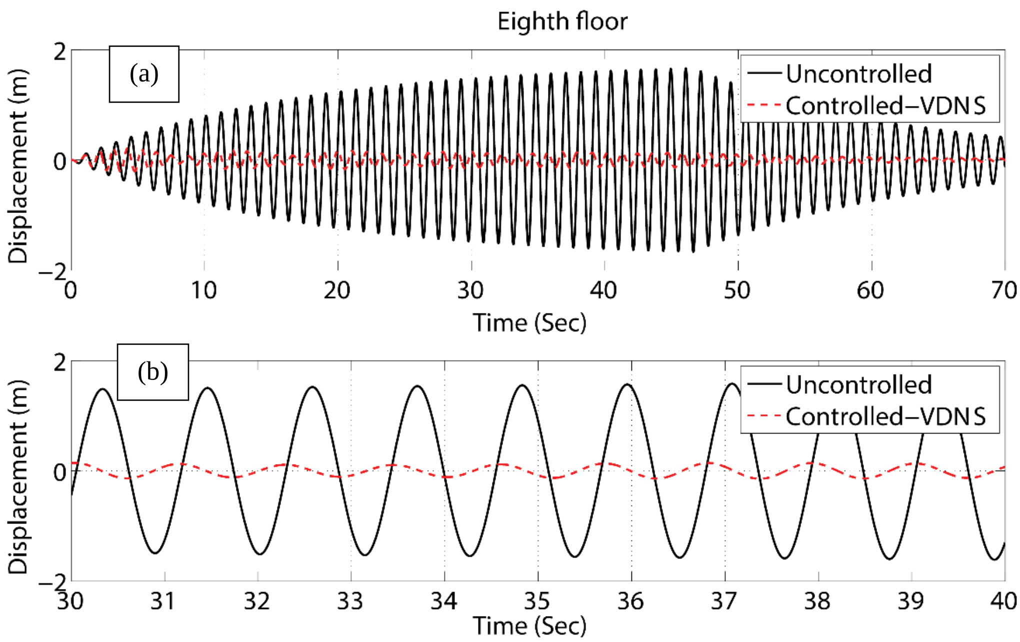

Figure 7: Comparison of the 8th floor velocity; (a) full-time history, (b) zoomed view.

Furthermore, fifth floor and eighth floors responses are evaluated and similar results are obtained. Hence the above indicated statement holds for all of the individual floor. Additionally, to observe the stability of the control closed-loop the displacement and velocity versus control force hysteresis is presented in Figures 8-9. And the results confirm that an optimal control force was implemented in real-time. The colour coding of Figures 2-7 remains same, means the black line indicates the uncontrolled displacement and the dotted red line represents the controlled one.

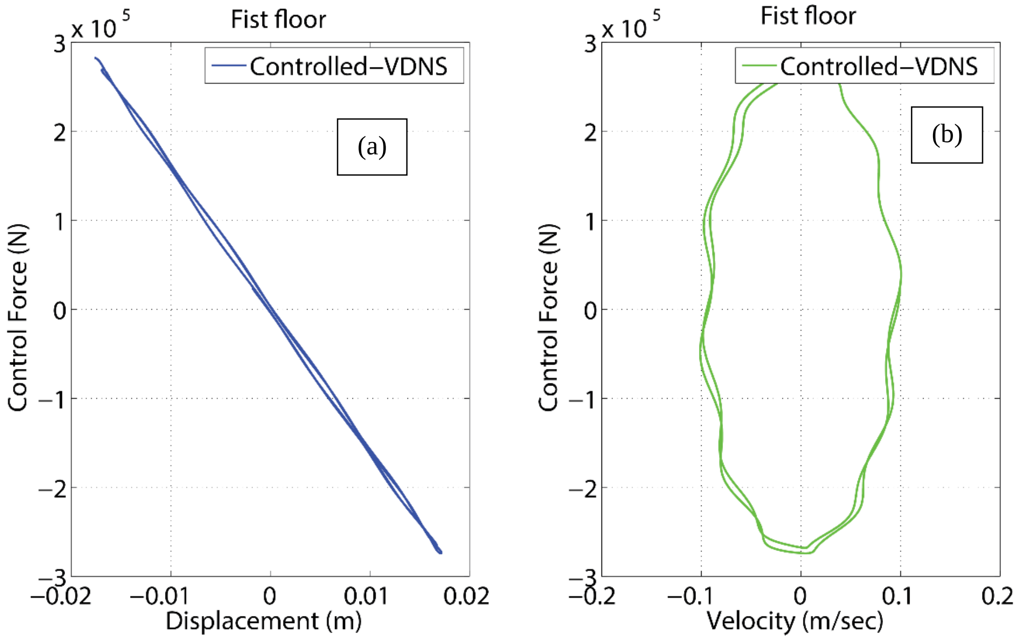

Figure 8:The 1st floor (a) displacement and (b) velocity versus control force hysteresis.

It needs to be mentioned that the stable control force was implemented based on the current displacement and velocity information. To do this end, the SIMULINK® was used to ensure nearly real-time implementations. And the estimated responses confirmed that the real-time information helps to reduce the vibration optimally. Also the effect of negative stiffness is visible in the displacement versus control force hysteresis. Further, the velocity versus control force confirms the active actuation was successfully implemented.

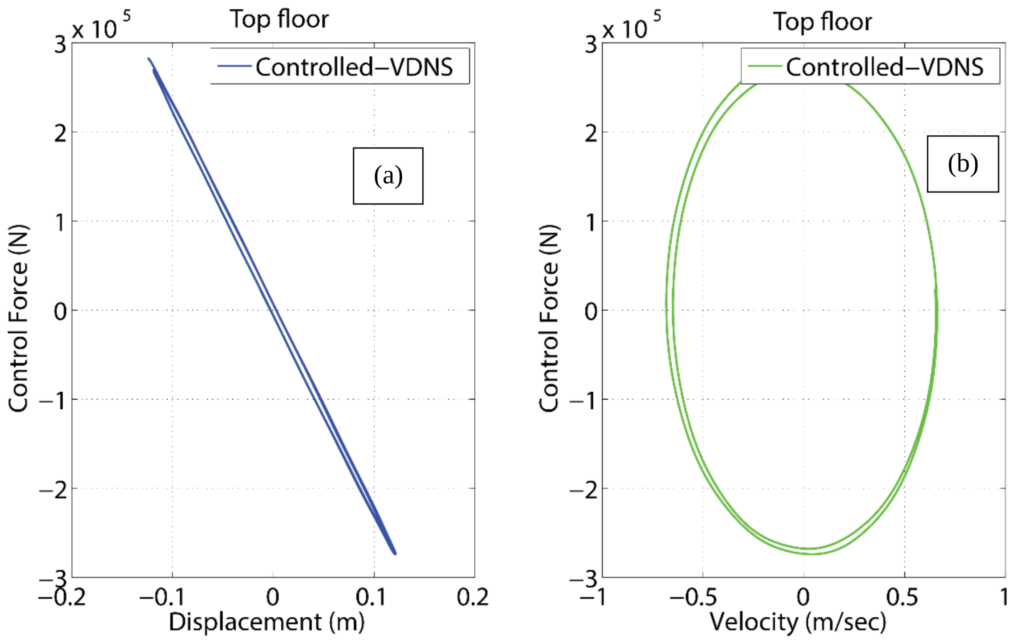

Figure 9:The 10th floor (a) displacement and (b) velocity versus control force hysteresis.

4. CONCLUSIONS

The possibilities of real-time vibration mitigation and control via a simplified control law e.g. VDNS is investigated by employing a 10-storied frame structure. The aforementioned control law was combined with UKF. Two dampers are used, the first damper was placed at the first floor level and the second damper was placed at the top floor level. The simulations are performed via MATLAB/SUMILINK® by considering a nearly real-time implementation. The responses are evaluated and it is observed that the VDNS control law is capable of reducing significant level of vibration. In addition to the real-time vibration reduction the studied approach has the possibility to update model in real-time. Also the investigated approach has the potential to deal with nonlinear system. Hence, the VDNS control law is recommended for its simplest structure and overall efficiency over LQR. The proposed approach is going to assist the monitoring the overall structural performances in real-time.

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