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ON THE USE OF ROBUST COMMAND SHAPING FOR VIBRATION REDUCTION DURING REMOTE HANDLING OF LARGE COMPONENTS IN TOKAMAK DEVICES

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ABSTRACT

This paper proposes to use robust command shaping methods for reducing the vibrations during remote handling of in-vessel components. The need of deriving efficient vibration control strategies for a safe transportation of large and heavy payloads during maintenance procedures in nuclear fusion reactors is the main motivation behind this work. The approach shapes the reference motion command to the component such that the vibratory modes of the system are canceled. We perform the dynamic simulations of a large in-vessel component of the DEMOnstrating fusion power reactor during a remote handling operation. The simulations shows that the method is a possible solution to reduce the vibrations induced by the motion, in both the transient and residual phases. The benefits introduced by command shaping make the method promising towards building control framework for remote handling of in-vessel components in various tokamak devices.

1 INTRODUCTION

Accurate motion of large and heavy components is a challenging control problem because it often results in high levels of vibrations. This is particular evident in remote handling of in-vessel components inside advanced tokamak devices [1, 2].

Classic feedback control methods can be used to reduce the vibrations, but they are usually expensive. As a matter of fact, they require sensors information, significant control power and dynamic model of the system to be controlled.

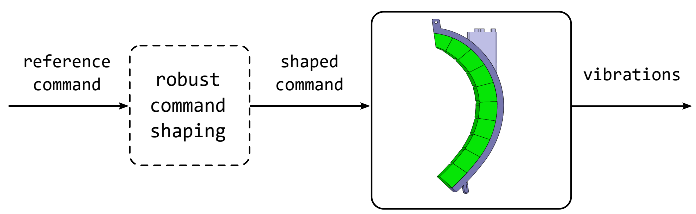

FIGURE 1: FRAMEWORK FOR HANDLING LARGE COMPONENTS USING ROBUST COMMAND SHAPING.

However, if not properly designed, then feedback may lead to instability of the system. Conversely, command shaping methods [3] are based on a feedforward strategy, which shapes the reference command such that the vibratory modes of the system are canceled. In these methods, the reference signal is convolved with a series of impulses, whose amplitude and time locations are determined by solving a set of constraint equations. The main advantage of command shaping is that the constraint equations use only estimates of the system natural frequencies and damping [3]. However, classical command shaping can be sensitive to parameter estimation, i.e. if the natural frequencies and damping are not well estimated or they are time−varying, then the effectiveness of the method is reduced. One possible strategy is to use robust command shaping techniques [4], which allow a significant vibration reduction even in presence of uncertainty in the system parameters.

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This paper presents a framework for remote handling of large in-vessel components using robust command shaping. This framework allows reducing the transient and residual vibrations during remote handling procedures. The process is illustrated in Fig. 1. A reference motion command is filtered out by a robust command shaper so as to generate a shaped command for the large component with the objective of reducing the induced vibrations. We validate the approach by simulating the motion of a large in-vessel component of the DEMOnstrating fusion power reactor (DEMO), namely the outboard blanket segment, according to the sequence of maneuvers which have been planned for its removal from the vacuum vessel. The blanket is the component responsible for: (i) ensuring self-sufficiency of the fusion reactor with regard to tritium; (ii) maximizing the net efficiency of the power plant; (iii) acting as a radiation barrier for the components behind it. Finally, the vibration suppression capability of the framework is proven by comparing the amplitude of the transient and residual vibrations during the dynamic simulations of the component's motion in the unshaped and shaped cases.
The rest of the paper is organized as follows. In the next Section we review related work in the field. In Section 3 we present an overview on command shaping methods. In Section 4 we validate the framework for vibration reduction in a meaningful case study, the motion of the DEMO outboard blanket segment. Section 5 concludes the paper and discusses future developments.

2 LITERATURE REVIEW

The first work on robust command shaping can be found in the derivative methods of Singer and Seering [5]. They added in the shaper design process a constraint which forces the derivative of the percentage residual vibration with respect to the natural frequency to equal zero. A different approach was developed by Singhose et al. in [6], where they introduced the concept of extra-insensitive shapers. Here, the constraint of zero vibration at the modeling frequency was replaced with a constraint which limits the vibration to a tolerable value. After, Singhose et al. [7] developed another robust technique, called specified-insensitive shaping, which suppresses the vibrations in a specified range of frequencies . Recently, a predictive approach was used by Grazioso et al. [8] to derive a robust closed-loop shaper with the same vibration suppression capability of existing robust shapers, but without increasing the rise time of the command.
The use of command shaping as a control scheme for vibration suppression has been proved in many application domains as: industrial robots [9]; overhead cranes [10]; fueling transporting system in nuclear plants [11].
This paper introduces the command shaping in the DEMO remote handling. As a first investigation, we use the derivative methods. The results of the framework in terms of vibration suppression capability make the method attractive in safer maneuvering of large components with minimal modeling effort.

3 COMMAND SHAPING METHODS

Command shaping methods convolve the reference command with a sequence of impulses. The timing and amplitude of the impulses are determined by solving a set of constraint equations involving only an estimates of the system frequencies and damping. The rise time of the command is lengthened by the duration of the shaper.

The primary design constraint is a limit on the amplitude of vibration caused by the system. If we assume the system modeled as an underdamped second-order system, we can use the percentage residual vibration (PRV) index as parameter to be constrained [12]. The PRV value is indicated as

$$V(\omega,\zeta) = e^{-\zeta\omega t_n}\sqrt{[C(\omega,\zeta)]^2+[S(\omega,\zeta)]^2} \tag{1}$$

with

$$C(\omega,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i}\cos\left(\omega t_i\sqrt{1-\zeta^2}\right) \tag{2}$$

$$S(\omega,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i}\sin\left(\omega t_i\sqrt{1-\zeta^2}\right) \tag{3}$$

where ω is the natural frequency of the system, ζ is the damping ratio, A_i and t_i are the $i-$th impulse amplitude and timing, respectively. Equation 1 represents the level of vibration induced by an impulse sequence given any value of frequency and any damping ratio less than one. A constraint on the residual vibration amplitude can be formulated by setting $V(\omega,\zeta)$ less than or equal to a certain level of residual vibration at the modeled natural frequency and damping ratio.

Since in real applications the system parameters needed to design the input shaper are not known exactly, an additional equation constraint regarding the robustness of the method can be formulated. One approach is to set the derivative of (1) with respect to the frequency ω, to be less or equal to a tolerable value tol as

$$\frac{\partial}{\partial\omega}V(\omega,\zeta) \leq tol \tag{4}$$

Further robustness can be achieved by setting additional high-order derivatives, always with respect to the frequency ω, to be less than or equal to a tolerable value.

Finally, a constraint must be formulated to ensure that the shaped command produces the same rigid-body motion of the unshaped command. Thus, to satisfy this requirement, the impulse amplitudes must sum to one as

$$\sum_{i=1}^{n} A_i = 1 \tag{5}$$

In the following, we present the amplitude and timing location expressions for the zero vibration (ZV), the zero vibration and derivative (ZVD), the zero vibration and double derivative (ZVDD) and the zero vibration and triple derivative (ZVDDD) input shapers.

3.1 ZV input shaper

The ZV input shaper is obtained by setting (1) equal to zero. The amplitude and time locations of the impulses take the form

$$\mathrm{ZV} = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & \frac{1}{2}\tau_d \end{bmatrix} \tag{6}$$

where τ_d is the damped vibration period and $K = e^{-\zeta\pi/\sqrt{1-\zeta^2}}$.

3.2 ZVD input shaper

The ZVD input shaper is obtained by setting (1) and its first derivative with respect to ω equal to zero. The amplitude and time locations of the impulses take the form

$$\mathrm{ZVD} = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+2K+K^2} & \frac{2K}{1+2K+K^2} & \frac{K^2}{1+2K+K^2} \\ 0 & \frac{1}{2}\tau_d & \tau_d \end{bmatrix} \tag{7}$$

3.3 ZVDD input shaper

The ZVDD input shaper is obtained by setting (1) together with its first and second derivative with respect to ω equal to zero. The amplitude and time locations of the impulses take the form

$$\mathrm{ZVDD} = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{P} & \frac{3K}{P} & \frac{3K^2}{P} & \frac{K^3}{P} \\ 0 & \frac{1}{2}\tau_d & \tau_d & \frac{3}{2}\tau_d \end{bmatrix} \tag{8}$$

where $P = 1 + 3K + 3K^2 + K^3$.

3.4 ZVDDD input shaper

The ZVDDD input shaper is obtained by setting (1) together with its first, second and third derivative with respect to ω equal to zero. The amplitude and time locations of the impulses become

$$\mathrm{ZVDDD} = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{Q} & \frac{4K}{Q} & \frac{6K^2}{Q} & \frac{4K^3}{Q} & \frac{K^4}{Q} \\ 0 & \frac{1}{2}\tau_d & \tau_d & \frac{3}{2}\tau_d & 2\tau_d \end{bmatrix} \tag{9}$$

where $Q = 1 + 4K + 6K^2 + 4K^3 + K^4$.

3.5 Test example

As an illustrative example, let us consider a mechanical system with $\zeta = 0$ and $\tau_d = 2\,\mathrm{s}$, subject to a rectangular velocity command of $1\,\mathrm{ms}^{-1}$ for $5\,\mathrm{s}$. The shaped commands, according to the theory described in this Section, are given by Fig. 2. Here, we can see the convolution processes involving from two to five impulses, respectively from ZV to ZVDDD shapers.

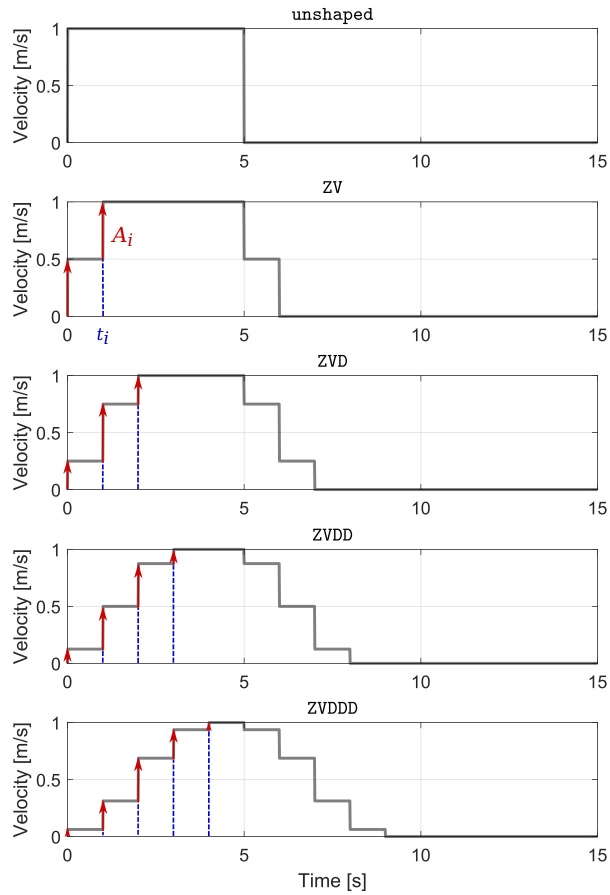

FIGURE 2: INPUT SHAPING CONVOLUTION PROCESS.

4 CASE STUDY

The case study simulates the motion of the right outboard blanket segment (ROBS) while performing the sequence of maneuvers which have been planned for its removal process.

4.1 Description of the model

The ROBS geometric model is illustrated in Fig. 3. A six degrees-of-freedom joint applied in 1 allows simulating the free motion of the ROBS in three-dimensional space. The initial configuration of the meaningful points of the mechanical component (1, central point of the blanket interface; 2, center of gravity point; 3, tip point) is given by Table 1. All the quantities are expressed in the inertial reference frame Oxyz, whose origin is the datum for tokamak models. As a first investigation, we perform a rigid-body analysis. The ROBS dynamic parameters have been estimated from the CAD model, and they are given in Table 2.

The sequence of maneuvers which have been planned for the ROBS removal process involves a sequence of point-to-point configurations, as given in Table 3. In order to generate a motion trajectory for the dynamic simulation, we linearly interpolate this sequence by assuming that each successive configuration is reached in 2 s.

4.2 Design of the shapers

The shapers have been designed by approximating the natural frequency of the ROBS with the linearized frequency of a single pendulum-like system, given by

$$\omega = \sqrt{g/L} \tag{10}$$

where g is the modulus of the acceleration gravity vector and L is the distance between the points 1 and 2, measured along the $z-$direction. The system has

$$\zeta = 0 \tag{11}$$

$$\tau_d = 2\pi/\omega \tag{12}$$

Then, equations 6–9 have been used to design the shapers.

4.3 Simulations

In the dynamic simulations, the joint in 1 is actuated in its positional part according to the motion trajectory generated from the point-to-point configurations for the ROBS removal. The overall trajectory lasts 18 s. In order to appreciate the residual vibrations, the motion of the system is observed for 40 s. The system is subject to gravity downward $z-$ axis.

Figure 4 plots, in the inertial reference frame Oxyz, the three components of displacements of the point 3, i.e. the tip of the ROBS, for the unshaped case. The interval 0–18 seconds refers to the transient phase, while the interval 18–40 seconds refers to the residual phase. Therefore, the simulations have been performed using the command shaping framework, for the cases ZV, ZVD, ZVDD and ZVDDD.

4.4 Comparison

To compare the performances of the different shapers, we define a vibration suppression index as

$$\rho[\%] = \frac{|\alpha_s - \alpha_u|}{\alpha_u} \cdot 100 \tag{13}$$

where α_s is the amplitude of the maximum vibration in the shaped case, while α_u is the amplitude of the maximum vibration in the unshaped case.

Figure 5 reports the vibration suppression indices for all the shapers involved in this study. The index ρ has been computed for both the transient and residual vibrations, for the three components of displacements of the point 3. Further, we indicate with μ the average of the three indices obtained for x, y and z.

4.5 Outcomes and Discussion

In this section we analyze and discuss the results obtained from the case study.

The ROBS, actuated in point 1, behaves as a pendulum system: the amplitudes of its vibrations are critical if we consider the displacements of the tip point 3 resulting from unshaped motion commands. This situation is illustrated in Fig. 4.

The proposed framework makes use of feedforward control actions to shape the reference commands so as to provide a certain degree of vibration reduction. As it can be noticed from Fig. 5, this simple feedforward action reduces the vibrations up to $\sim$70% in some cases. Since the command shapers have been designed using the PRV index (1) which constraints the residual vibrations, the ρ values are higher for the residual vibrations. For all cases, the $y-$ displacement is affected the most by the shaping process. The relatively low average indices obtained for the transient vibrations are due to the presence in μ of the $z-$ component, which obviously is not affected to vibrations of high absolute amplitude even in the unshaped case. By progressively increasing the robustness, we can see that the vibration suppression index improves slightly: this happens because the distance L is constant for the duration of the simulation, since the ROBS is actuated in point 1 and we are considering a rigid-body analysis. Indeed, in this case the progressive robustness helps only if the design frequency of the shaper is different from the actual frequency of the system. In a soft-body simulation, robustness will help more since here the distance L will be time-variant, due to the mechanical deformation of the component.

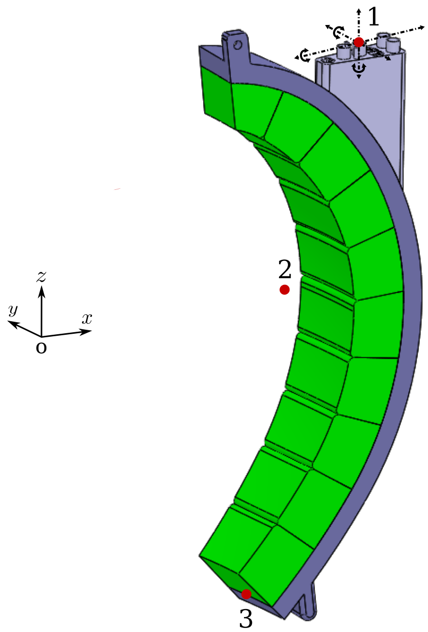

FIGURE 3: GEOMETRIC DESCRIPTION OF THE MODEL.

TABLE 1: POINTS IN THE INITIAL CONFIGURATION.

	x [m]	y [m]	z [m]
1	11.125	3.153	4.950
2	10.588	3.528	0.210
3	9.389	3.193	-4.839

What is important to point out is that the proposed framework is able to provide trajectories that inherently prevents vibrations of high amplitude in the large component to be transported. Since in point 1 will ideally be attached the end-effector of a manipulator for the ROBS maneuvers, the trajectories of point 1 turn out to be the operational space trajectories for the manipulator [13]. Hence, this framework could be a useful tool to generate safer operational space trajectories, that after needs to be mapped in the joint space of the manipulator.
Our aim is to extend the proposed framework to handle flexibility, so as to generate even safer trajectories for remote handling of large components, using multi-mode robust shapers.

5 CONCLUSIONS

Robust command shaping have been proposed to reduce the vibrations in maneuvering the DEMO outboard blanket segment, during a remote maintenance procedure. The control framework allowed reducing the vibrations by ∼20% for the transient phase and by ∼50% for the residual phase. The results achieved in this work state that robust command shaping methods could represent a possible feedforward action to vibration control of in-vessel components during remote handling operations.

Future works of the authors will include a feedback action to enhance the suppression vibration capability in the transient phase. Further, the remote handling framework will be endowed with the possibility to account for flexibility [14–16] by developing multi-mode robust shapers for distributed system.

TABLE 2: ROBS DYNAMIC PARAMETERS. m $[1 \times 10^3$ kg]; I $[1 \times 10^4$ kgm$^2]$

m	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
17.8	36.5	214.3	222.9	66.6	3.98	1.16

TABLE 3: CONFIGURATIONS FOR THE ROBS REMOVAL

	1_x [m]	1_y [m]	1_z [m]
0	11.125	3.153	4.950
1	11.125	2.981	4.952
2	11.125	3.153	4.950
3	11.107	3.153	5.099
4	11.107	2.053	5.099
5	11.009	2.034	5.893
6	11.191	2.041	5.698
7	11.191	2.041	11.297
8	11.967	2.041	12.639
9	11.967	2.041	21.239

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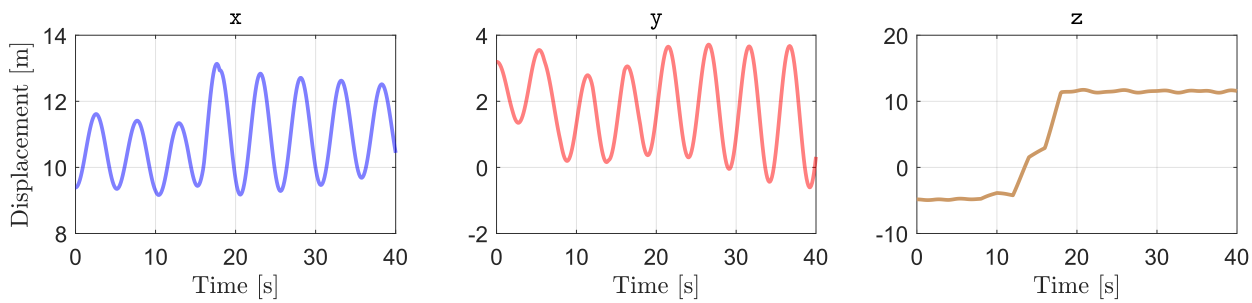

FIGURE 4: UNSHAPED RESPONSE OF THE ROBS TIP.

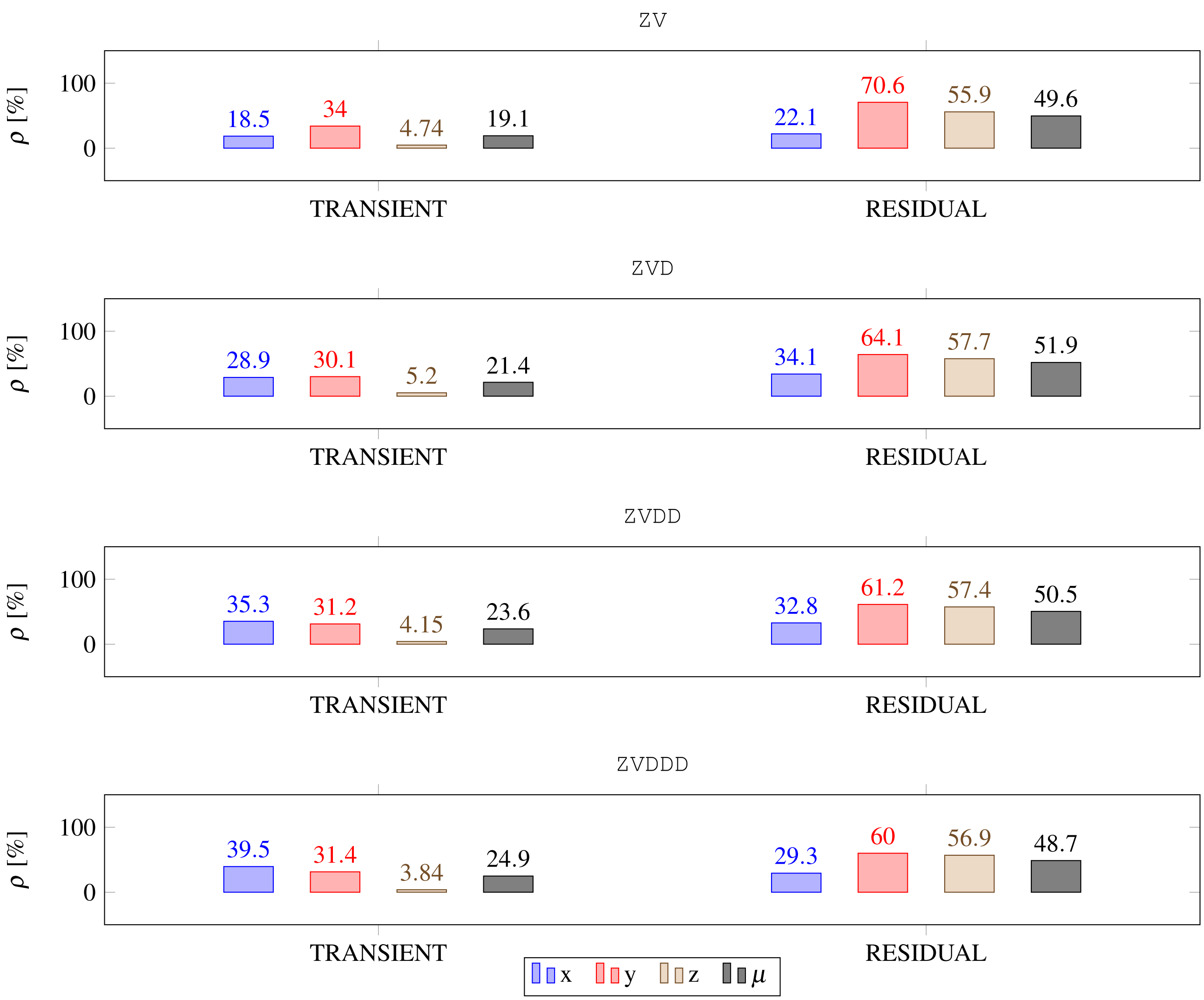

FIGURE 5: VIBRATION SUPPRESSION INDEX FOR THE DIFFERENT SHAPERS.

REFERENCES

[1] Loving, A., Crofts, O., Sykes, N., Iglesias, D., Coleman, M., Thomas, J., Harman, J., Fischer, U., Sanz, J., Siuko, M., et al., 2014. "Pre-conceptual design assessment of demo remote maintenance". *Fusion Engineering and Design,* ***89***(9), pp. 2246–2250.

[2] Coleman, M., Sykes, N., Cooper, D., Iglesias, D., Bastow, R., Loving, A., and Harman, J., 2014. "Concept for a vertical maintenance remote handling system for multi module blanket segments in demo". *Fusion Engineering and Design,* ***89***(9), pp. 2347–2351.

[3] Singhose, W., 2009. "Command shaping for flexible systems: A review of the first 50 years". *International Journal of Precision Engineering and Manufacturing,* ***10***(4), pp. 153–168.

[4] Vaughan, J., Yano, A., and Singhose, W., 2008. "Comparison of robust input shapers". *Journal of Sound and Vibration,* ***315***(4), pp. 797–815.

[5] Singer, N. C., and Seering, W. P., 1990. "Preshaping command inputs to reduce system vibration". *Journal of dynamic systems, measurement, and control,* ***112***(1), pp. 76–82.

[6] Singhose, W., Seering, W., and Singer, N., 1994. "Residual vibration reduction using vector diagrams to generate shaped inputs". *Journal of Mechanical Design,* ***116***(2), pp. 654–659.

[7] Singhose, W. E., Seering, W. P., and Singer, N. C., 1996. "Input shaping for vibration reduction with specified insensitivity to modeling errors". *Japan-USA Sym. on Flexible Automation,* ***1***, pp. 307–13.

[8] Grazioso, S., Di Gironimo, G., Singhose, W., and Siciliano, B., 2017. "Input predictive shaping for vibration control of flexible systems". In 2017 IEEE Conference on Control Technology and Applications, IEEE, pp. 305–310.

[9] Zhao, Y., Chen, W., Tang, T., and Tomizuka, M., 2016. "Zero time delay input shaping for smooth settling of industrial robots". In 2016 IEEE International Conference on Automation Science and Engineering, IEEE, pp. 620–625.

[10] Singhose, W., Porter, L., Kenison, M., and Kriikku, E., 2000. "Effects of hoisting on the input shaping control of gantry cranes". *Control engineering practice,* ***8***(10), pp. 1159–1165.

[11] Shah, U. H., and Hong, K.-S., 2014. "Input shaping control of a nuclear power plants fuel transport system". *Nonlinear Dynamics,* ***77***(4), pp. 1737–1748.

[12] Kozak, K., Singhose, W., and Ebert-Uphoff, I., 2006. "Performance measures for input shaping and command generation". *Journal of dynamic systems, measurement, and control,* ***128***(3), pp. 731–736.

[13] Siciliano, B., Sciavicco, L., Villani, L., and Oriolo, G., 2010. *Robotics: modelling, planning and control*. Springer Science & Business Media.

[14] Grazioso, S., Sonneville, V., Di Gironimo, G., Bauchau, O., and Siciliano, B., 2016. "A nonlinear finite element formalism for modelling flexible and soft manipulators". In 2016 IEEE International Conference on Simulation, Modeling, and Programming for Autonomous Robots, IEEE, pp. 185–190.

[15] Grazioso, S., Di Gironimo, G., and Siciliano, B., 2018. "Analytic solutions for the static equilibrium configurations of externally loaded cantilever soft robotic arms". In 2018 IEEE International Conference on Soft Robotics, IEEE.

[16] Grazioso, S., Di Gironimo, G., and Siciliano, B. "From differential geometry of curves to helical kinematics of continuum robots using exponential mapping". In *Advances in Robot Kinematics 2018*. Springer.