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Active Multidimensional Vibration Absorbers for Light Robots

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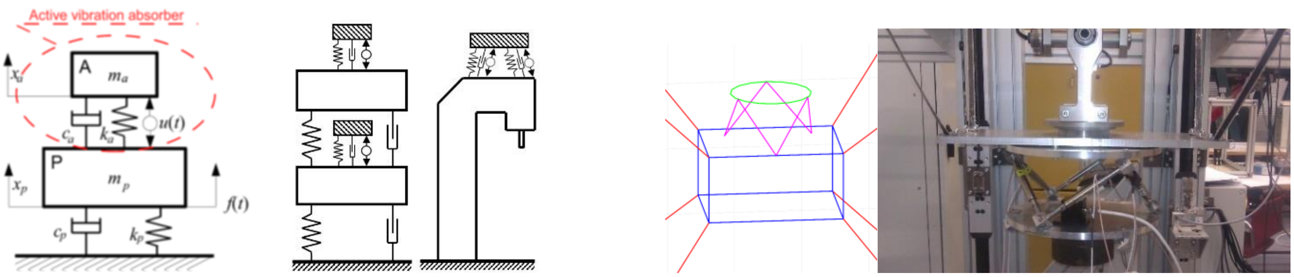
ABSTRACT — *This paper deals with the research of multidimensional vibration absorbing of flexible mechanisms of machines, such as light robots or cable structures. Due to its design, those structures are able to cover large workspaces, but their mass/stiffness ratio does not allow high accuracy of the end-effector, when excited with external force. To damp those vibrations, various passive or active additional mechanical structures are being used. The active vibration absorbers are usually designed as one or more single DoF mechanisms, while multi DoF active platforms are often used as active vibration isolators. The goal is to suppress vibrations of the end-effector using additional single body-spring multi-DoF absorber with active elements, in order to damp vibrations through wide frequency spectrum and in various robot positions, since its dynamical characteristics can vary rapidly through the workspace. Considering three-dimensionality of the structure, there is high complexity of the problem and optimizations. The primary demonstrator of the active 6DOF vibration absorber consists of the regular cubic truss created from six piezoelectric actuators. The voice-coil actuators have been chosen and purchased for further development because of higher flexibility of primary passive tuning of the absorber by parallel springs. The primary demonstrator has been mounted and tested on the cable driven platform, however the main target of the research is seen in the branch of serial robots.*

1 Introduction

During the last decades there has been an intensive development in production machines and robots in order to increase their production efficiency. Many concepts have been investigated including the usage of new types of kinematics [1], non-traditional usage of machines using special control algorithms (e.g. industrial robots used for drilling) [2] and many others. The development of the accurate motion control of the end-effector is one of the main targets of functional optimization of such machines. The opened question is what can be achieved through accurate measurement of the machine's end-effector position and its subsequent use to compensate for control loop errors between actuators and the end-effector. The counterpart of the accurate motion control of the end-effector is the strategy of controlled vibration suppression [3]. The controlled vibration suppression [3] can be realized by added damping, vibro-isolation, vibro-compensation or vibro-absorption principles. Further, we differentiate between active (controlled energy influx) and semi-active (controlled energy dissipation) approaches [4] [5]. The range of vibration suppression applications span from actively controlled vibration of aircraft wings, broadcasting towers, radars, telescopes, active damping on regenerative chatter instability for a turning operation [6] all the way to cable bridges stabilization.

The idea of the passive vibration absorber connected to the primary mechanical structure to suppress its vibrations is known and patented for approximately one hundred years. The main benefit of this passive approach is that no (or minimal) energy needs to be exerted to damp the oscillations. On the other hand, the frequency band, where the absorber suppresses the vibrations efficiently, is relatively narrow, being centered at the natural frequency of the absorber. This inefficiency can partly be mitigated by tuning the mechanical parameters of the absorber, particularly the stiffness and mass of the absorbers, e.g. [7] with method to achieve more broad-band suppression. Substantially better results can be achieved by an active approach, i.e. utilizing the controlled active actuators. The active vibration absorbers are usually designed as single DOF mechanisms (Fig. 1a)) even in the multi DOF case where several SDOF absorbers are used (Fig. 1b)). On the other hand, the multi DOF active platforms (e.g. of the Stewart parallel mechanism type) are often used as active vibration isolators.



a) SDOF active absorber b) multi SDOF and MDOF version c) demonstrator of 6DOF absorber on cable driven platform

Fig. 1: Active vibration absorber concepts and demonstrator

This concept is inspiration of the primary demonstrator of the multidimensional 6DOF vibration absorber (Fig. 1c)) using regular cubic truss created from six piezoelectric stack actuators. The control of the active absorber can be designed using different strategies including LQG, LQR, H_∞/H_2, model predictive control and others. The interesting alternative is a so called "Delayed Resonator" concept. In this method, the passive absorber is supplemented by an active feedback with the objective to turn the physical absorber to an ideal (undamped) absorber with natural frequency equal to the frequency to be suppressed. As a consequence, the vibrations at the given frequency are suppressed entirely, which is the key benefit. Several variants of this method have been developed and successfully tested [8], however many questions are open, especially non-collocated examples and usage for more complex structures. The concept of multi-level mechanisms brings the potential to improve dynamical properties of the diverse lightweight robots and manipulators with large workspace. The primary end-effector should cover the full workspace while the superimposed secondary platform is capable to perform smaller but highly dynamic maneuvers [9], [10]. The cable driven robots and manipulators are an important but not the only representatives of such promising light machines. The usage of the secondary platform as the true end-effector [10] requires measurement of its absolute position e.g. by laser tracker (Fig.2). Unfortunately, such an operation is often very difficult to implement especially for the large workspaces in the complex industrial environment.

a) end-effector position feedback using laser tracker b) end-effector attached to the cable structure using piezo actuators

Fig.2: Secondary platform as a true end-effector

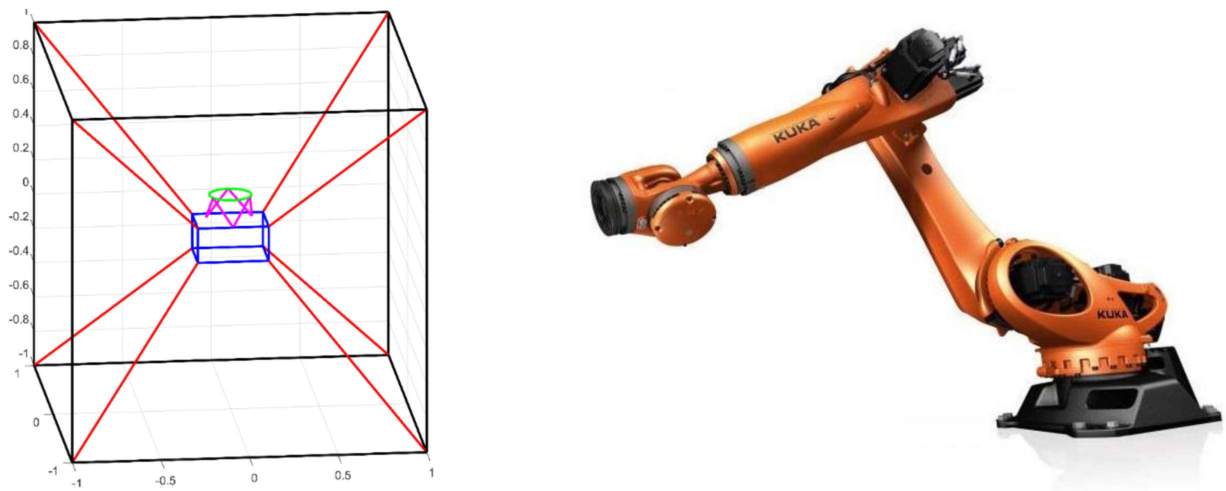
The usage of the secondary platform as an inertial base of the active multidimensional vibration absorber (Fig. 1c)) presents an alternative idea which needs less demanding and more robust local sensing e.g. by accelerometers or geophones. The necessity of usage of active version of MDOF absorber is emphasized by typically strong variability of eigenfrequencies and eigenmodes of such flexible robots and manipulators within their workspace.

2 Variants of robots for active vibration absorption

Those structures, that are light and capable of maneuvering through large workspace, are often most susceptible to vibrate due to external excitation, whether from e.g. end-effector drilling head or from simple inertial forces.

Parallel structure is usually stiff enough from its own design principle – and also operating in smaller workspace as well. The exception is cable parallel structure (Fig. 3a)), which can operate through enormous workspace as far as translation movements are considered. Since rotations of such a parallel structure is limited by its kinematics and cable vs. structure collisions, and direction of cables remains almost the same, there is not much of a rapid dynamical characteristics change of the system when moving through space. Vibrations of parallel cable structure, which is excited by external harmonic force of few constant frequencies, were successfully suppressed [11] using passive 6-DoF absorber optimized through mass and elements stiffness parameters.

On the other hand, serial robots come up with various eigenfrequencies and eigenvectors through different positions of the end-effector. That is over the possibilities of single passive absorber, even when single excitation frequency is considered. In this case, active vibration absorber needs to be implemented. The open questions is which type of feedback is sufficient and efficient to damp the main structure. In this paper, widely spread type of 6-DoF robot (Fig. 3b)) with 6 rotation constraints is used for simulations and for future experiments.



a) Cable parallel manipulator with 6-DoF active absorber

b) Serial robot manipulator with 6 rotational constraints

Fig. 3: Examples of light-weight robots with parallel and serial structure

2.1 Considered serial robot model

In order to simulate experiments, mathematical model of flexible 6-DoF serial robot was developed (Fig. 4). It consists of 7 bodies – first body represents solid base and others are attached using rotational constraints in Z-X-X-Z-X-Z order, considering local Z-axis of each body along the length of the body. Whole system has 36 states and includes rotational flexibilities around all axes of every joint, along with slight relative damping.

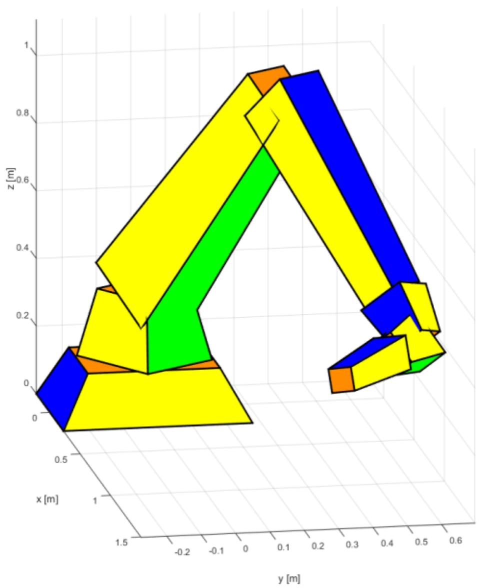


Fig. 4: serial 6-DoF robot simulation model in middle position

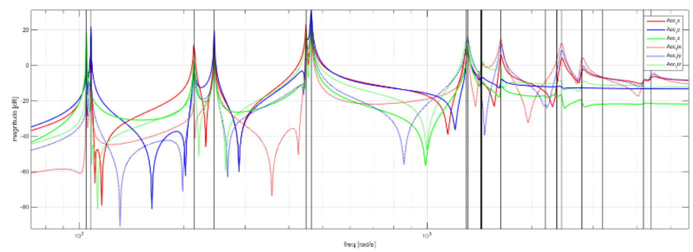


Fig. 5: serial robot - Bode diagram

[Hz]		
16,7	205,6	347,5
17,2	208,1	387,2
34,0	226,8	442,8
38,9	228,2	506,9
71,4	259,0	665,7
73,9	374,9	700,6

Tab. 1: Serial robot eigenfrequencies in middle position

Whole concept, including absorber design (see chapter 2.2), is suited for sake of further real experiment design. Total weight of robot is 165 kg and first 6 eigenfrequencies (Fig. 5, Tab. 1) are reasonably low for voice-coil actuators implementation. The simulation, optimization and control were performed in 5 different positions (Fig. 6) along the spiral stretching out trajectory. As mentioned before, dynamical characteristics are varying a lot along this trajectory, which can be seen in Tab. 2, that shows comparison of first six eigenfrequencies changing through trajectory.

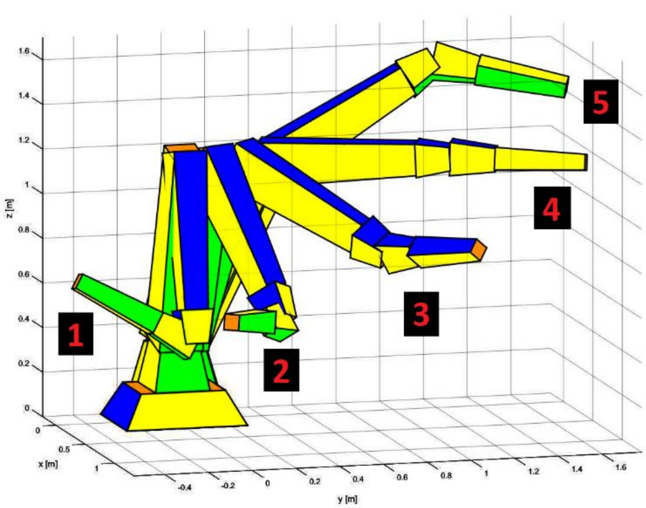


Fig. 6: Serial robot - simulated positions through trajectory

	1.p.	2.p.	3.p.	4.p.	5.p.
1.f.	26,2	20,9	15,8	13,4	12,5
2.f.	25,4	19,7	15,5	13,5	12,5
3.f.	34,4	30,7	34,2	39,5	48,9
4.f.	36,6	35,6	38,8	43,0	47,2
5.f.	65,7	70,7	77,0	83,5	91,4
6.f.	67,3	73,1	78,4	86,2	89,5

Tab. 2: First 6 eigenfrequencies through trajectory

2.2 Multi-DoF absorber design

Absorbers are commonly based on mass-spring structure, and both of those parameters are usually optimized even for active absorber, because at least roughly optimized passive absorber is most effective initial base for active actuation in order to achieve least energetic requirements potential.

Type of actuators depends on the use of absorber. E.g. piezo-actuators are effective for high frequencies (hundreds of Hertz). On the other hand, they have quite small range of operation (dozens, at most hundreds of micrometers), the stiffness is already included in its design and they are quite fragile. For sake of this paper and robot dynamics, voice-coils (Fig. 8) are more suitable, since they are capable of dozens of millimeters range and there is no initial stiffness between moving bodies, so the parallel springs design can be arbitrary. It only has initially greater mass, but that, when appropriately designed, can be counted as the absorber mass.

Simulations were done in collocated mode, so the end-effector is the one to be damped, externally excited and is also carrying the vibration absorber (Fig. 10). Due to various modes and general universality of the absorber implemented on serial robot, both the kinematical and dynamical design of additional structure leads to some kind of spatial symmetry. Cubical design (Fig. 7) of actuators is one of the proven structure concepts, since its elements are perpendicular to each other and form edges of imaginary cube.

Fig. 7: Preliminary version of absorber with piezo-actuators

Fig. 8: Voice-Coil actuator chosen for future prepared experiments

Initial optimization of dynamical properties was performed using basic local algorithms, since only one stiffness (applied to all 6 elements) and mass (eventually moments of inertia) are parametrized. Also, the position of this initial optimization was chosen in middle robot position. All of these conditions led to basic design of approx. 7 kg absorber mass and 3e5 N/m stiffness along 200 mm long elements.

The cost function was mainly based on end-effector 6-DoF accelerations minimalization, since all of the directions can be measured using one 3-dir., one 2-dir. and one 1-dir. appropriately located accelerometers. At first, opt. algorithm converged to the extremely heavy mass and stiff spring, so both robot and absorber were quite immune to the given external force impulse (300 N), since total mass was large and difficult to set in motion. On the other hand, addition of maximization of absorber movement to the cost function led to extremely large oscillation of few grams of mass. The right spot is to multiply this absorber movement maximization by its own mass, which leads to reasonable results mentioned above. Comparison of serials robot without and with attached passive absorber, while excited with force impulse (300 N) in its middle position, is shown in Fig. 9, through end-effector 6 axes accelerations.

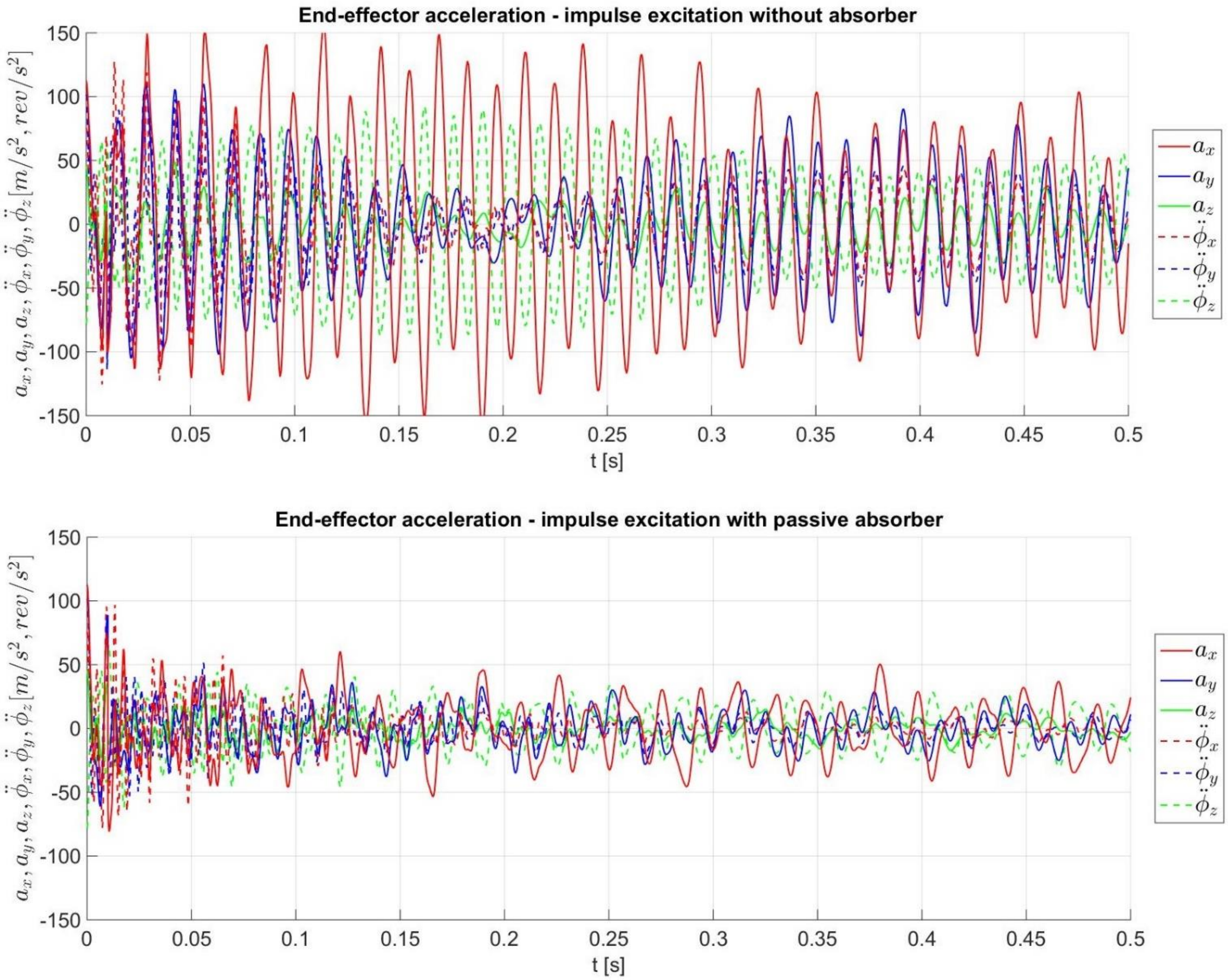


Fig. 9: non-absorbed (upper fig.) and passive-absorbed (lower fig.) vibration comparison

3 Active control

Feedback control of mechanical parallel structure leads most likely to some type of centralized control algorithm. From basic PID regulators, across H_∞ providing fixed-order controller as the result of optimization process, LQR, to already mentioned "Delayed Resonator" [8], etc.

3.1 LQR control

This paper deals with the LQR approach as an initial control design. Since dynamical properties vary through workspace, there is need of creating of multiple sets of ABCD matrices of local linearized state space models, in order to gain sufficient feedback commands. The way of ABCD matrices real-time providing, whether to create sufficiently dense multi-dimensional space of matrices in advance or to develop position dependent functions, remains an opened question.

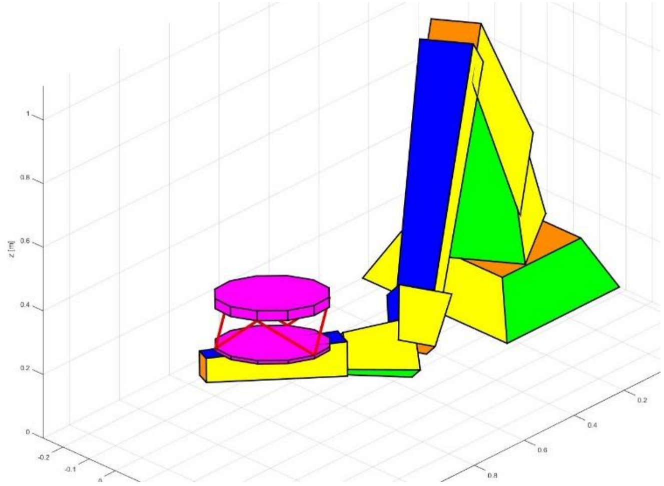


Fig. 10: multi-DoD absorber attached to the end-effector

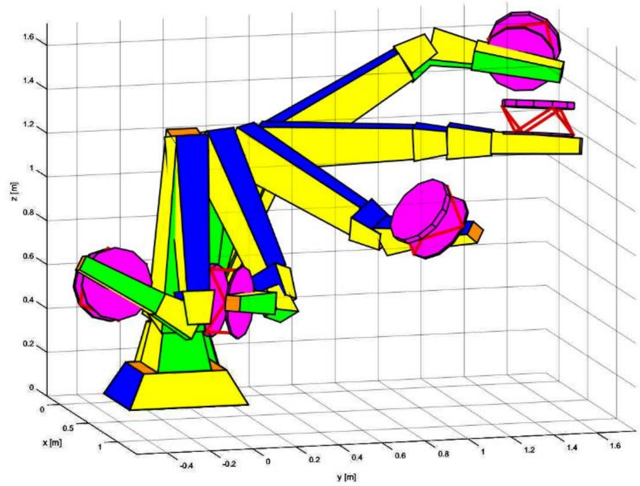


Fig. 11: absorber simulation positions to damp vibrations

For sake of initial simulation experiments, five positions through trajectory (Fig. 6) in workspace were linearized and transformed into Kalman feedback matrix K. Fig. 11 shows, that absorber orientation through the trajectory is highly diverse, which suggests the need of robot encoders real-time knowledge. Cost function was then in every case computed with respect to the end-effector acceleration minimalization and to the reasonable forces of voice-coil actuators, that were chosen for purpose of further real experiment. Voice-coils MGV52 AVM60-25 (see Fig. 8) should not exceed 30 N continuously and 120 N in peak.

3.2 Simulation results

External force impulse of 300 N is considered with constant direction with respect to the local system of the end-effector, since it simulates e.g. force excitation due to attached drill-head or some other work supply. Detailed results of non-absorbed, passive-absorbed and active-absorbed vibrations are shown in Fig. 12 along with input forces provided by actuators. Rest of the positions are then shown in summary Fig. 13 only in non-absorbed vs. active-absorbed comparison. In most cases, 90% of vibration were suppressed in about 0.1 seconds.

Another simulation test was performed using chirp excitation force in the spectrum range from 10 to 70 Hz, amplitude 50 N and duration of 10 seconds. Simulation results are shown in Fig. 14 in order of non-absorbed, passive-absorbed and active-absorbed vibrations, along with input forces provided by actuators.

In any of presented simulation results, the accelerations of the absorber did not significantly exceed maximal values of the robot acceleration without the absorber.

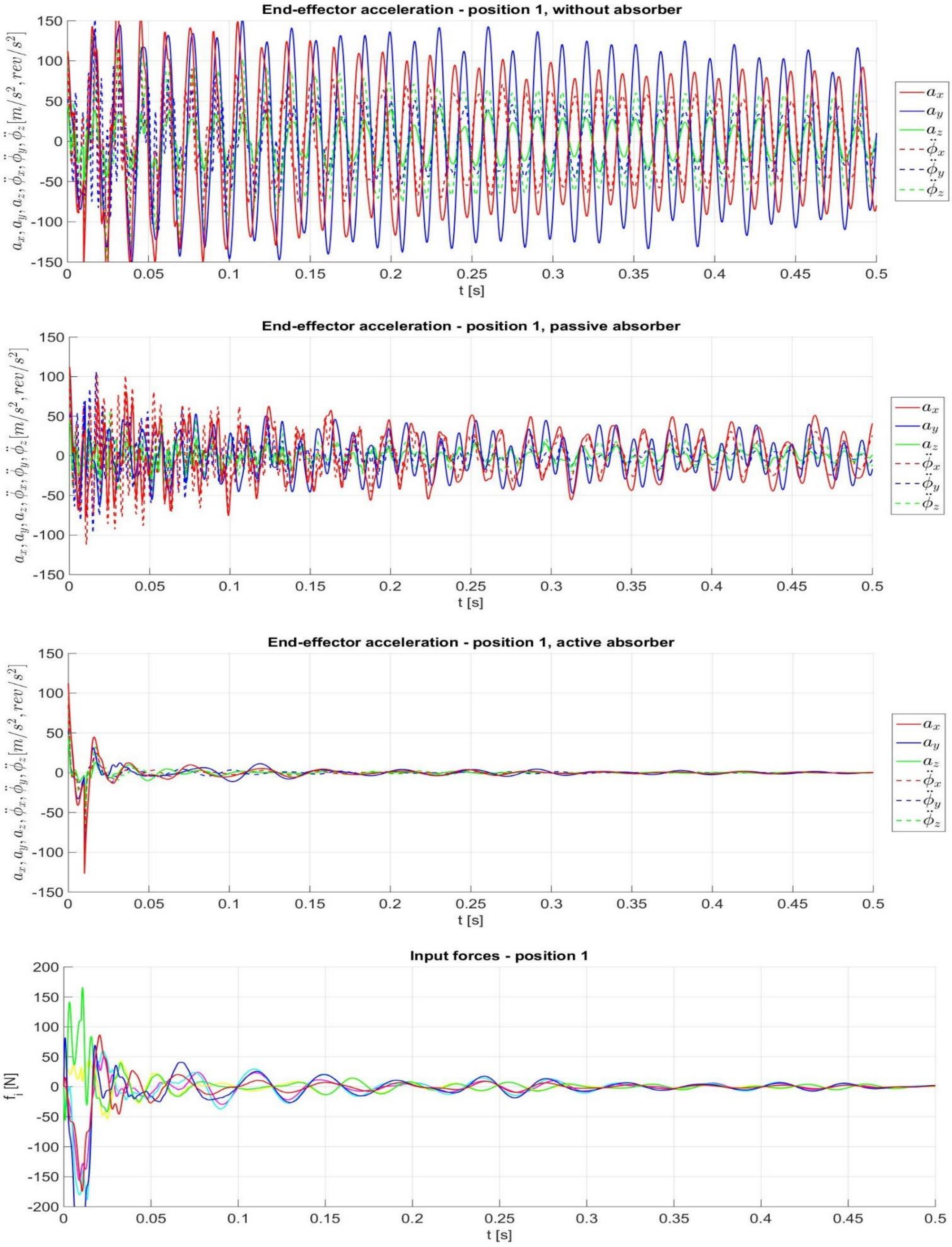


Fig. 12: end-effector vibration active damping - trajectory position 1

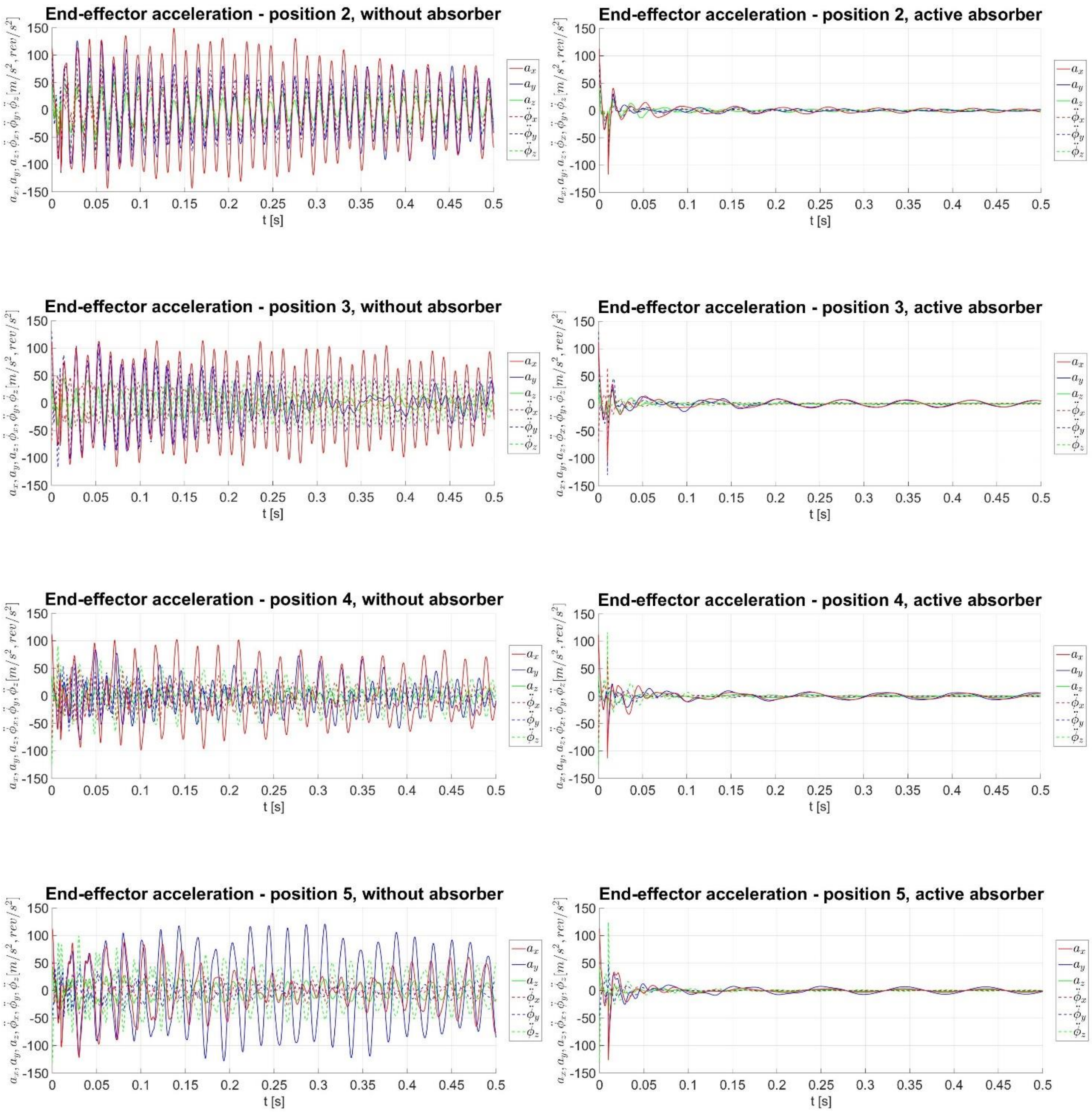


Fig. 13: end-effector vibration active damping – trajectory positions 2,3,4 and 5

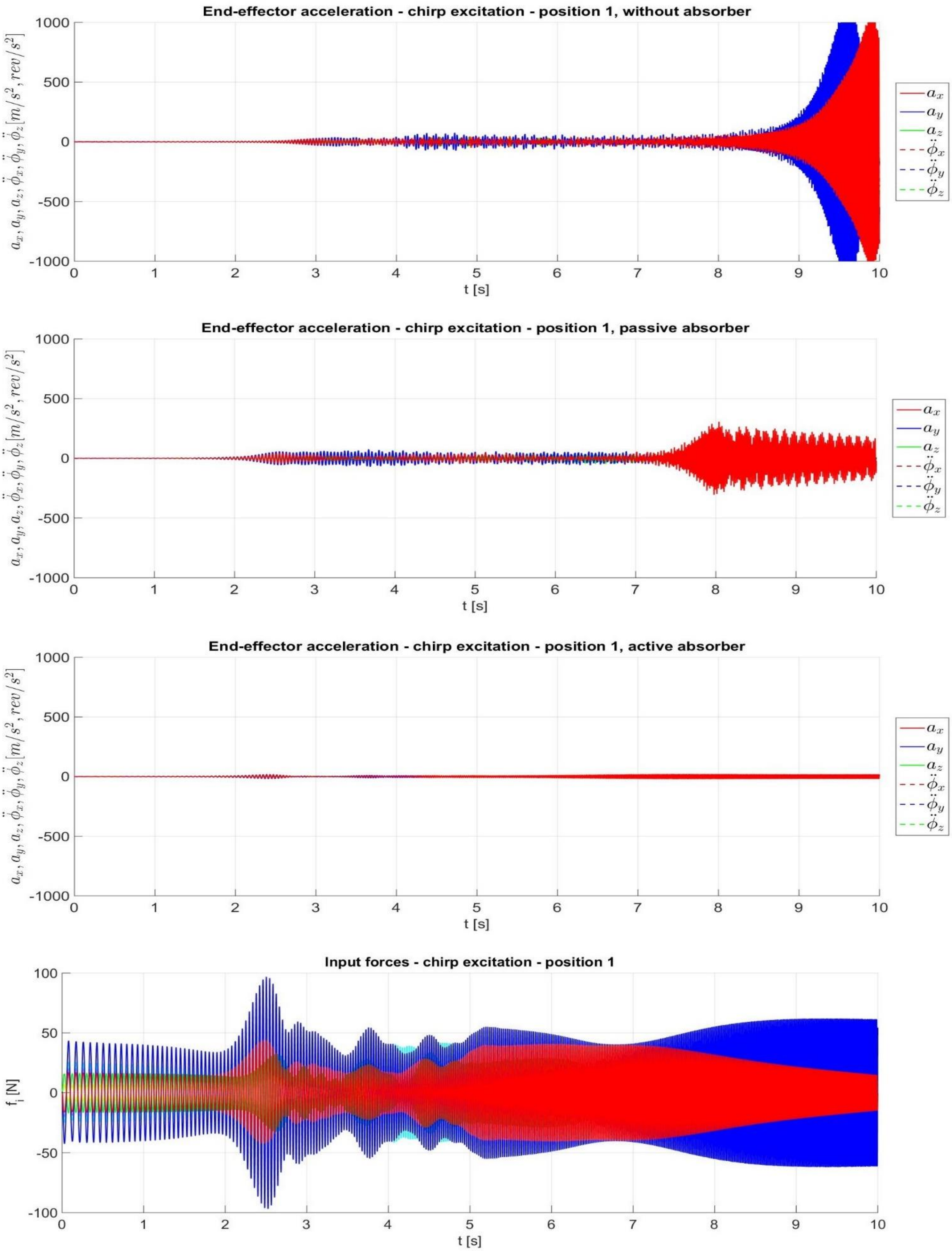


Fig. 14: end-effector vibration active damping – chirp excitation - trajectory position 1

4 Conclusions

The usage of active multidimensional vibration absorbing for flexible machines like serial robots or cable structures is a very interesting research topic. Due to its design, those structures are able to cover large workspaces, but their mass/stiffness ratio does not allow high accuracy of the end-effector, when excited with external force. To decrease those vibrations, various passive or active additional mechanical structures are being used. The active vibration absorbers are usually designed as one or more single DoF mechanisms, while multi DoF active platforms are often used as active vibration isolators. The goal is to suppress vibrations of the end-effector using additional single body-spring multi-DoF absorber with active elements, in order to damp vibrations through wide frequency spectrum and in various robot positions, since its dynamical characteristics can vary rapidly through the workspace. Considering three-dimensionality of the structure, there is high complexity of the problem and optimizations. The primary demonstrator of the active 6DOF vibration absorber consists of the regular cubic truss created from six piezoelectric actuators. The voice-coil actuators have been chosen and purchased for further development because of higher flexibility of primary passive tuning of the absorber by parallel springs. The primary demonstrator has been mounted and tested on the cable driven platform, however the main target of the research is seen in the branch of serial robots.

Serial robots, operating in large workspaces, are very widespread in all kinds of industry and better accuracy of the end-effector could make them even more universal. Production precision and use of new materials significantly increases static accuracy, but dynamical characteristics are still an issue. Basic approaches of accuracy increasing were discussed. Besides position feedback from the end-effector, use of an additional vibration absorber has no need to measure end-point positions in global coordinates, which can be very difficult or technically impossible task. Passive absorbers are not designed to reach accurate positions, but to damp dynamical vibrations, that, on the other hand, usually oscillate around the equilibrium. Possibilities of active approach were discussed and simulated in this paper. The active version of absorber is able to significantly reduce vibrations of the end-effector through various positions of the robot in workspace. The ratio of accuracy increases depends on possibilities of active actuators. There is only the need of robot's position information and the acceleration feedback from the end-effector, which can be easily implemented without large and badly embedded additional equipment. The presented study shows that the active vibration suppression of serial robot end-effector using active absorber equipped by available voice-coils is realizable.

The research of whole problematic is still in the process, so, many questions remain opened. The experiments with demonstrator equipped by the purchased voice-coils will be realized within the next year. The important open question for the further research is the necessary collocation level of absorber and end-effector bodies. The currently considered cubic hexapod structure mounted on the end-effector is only one possible variant.

Acknowledgements

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References

[1] D. Tesar and M. S. Butler, "Generalized modular architecture for robot structures," *Manufacturing Review,* vol. 2, no. 2, pp. 91-118, 1989.

[2] T. Olsson, M. Haage, H. Kihlman and et al., "Cost-efficient drilling using industrial robots with high-bandwidth force feedback," *Robotics and Computer-Integrating Manufacturing,* vol. 26, no. 1, pp. 24-38, 2010.

[3] A. Preumont, Vibration Control of Active Structures — An Introduction,, Dordrecht: Kluwer Academic Publishers, 2002.

[4] Z. Šika and M. Valášek, "Nonlinear Versus Linear Control of Semi-Active Vibration Isolation," in *EUROMECH Colloquium 455 on Semi-Active Vibration Suppression*, Prague, Czech Republic, 2004.

[5] Z. Šika, "Active and Semi-active Suppression of Machine Vibration", inaugural dissertation, CTU in Prague, 2005.

[6] A. Ganguli, A. Deraemaeker and A. Preumont, "Regenerative chatter reduction by active damping control," *Journal of Sound and Vibration,* vol. 300, no. 3-5, pp. 847-862, 2007.

[7] C.A.M. Verbaan, P.C.J.N. Rosielle and M. Steinbuch, "Broadband damping of non-rigid-body resonances of planar positioning stages by tuned mass dampers," *Mechatronics,* vol. 24, no. 6, pp. 712-723, 2014.

[8] T. Vyhlídal, N. Olgac and V. Kučera, "Delayed resonator with acceleration feedback – Complete stability analysis by spectral methods and vibration absorber design," *Journal of Sound and Vibration,* vol. vol. 333, no. 25, p. 6781–6795, 2014.

[9] X. Duan, Y. Qiu, J. Du, Z. Zhao and Q. Duan, "Real-time motion planning for the macro-micro parallel manipulator system," in *Proceedings of the IEEE International Conference on Robotics and Automation 2011*, pp. 4214-4219, Shanghai, China, 2011.

[10] Z. Šika, P. Beneš, M. Valášek, J. Volech and K. Kraus, "Cable Driven Spherical Mechanism Quadrosphere Enhanced by 3 DOF Piezo-actuated Platform," in *Proceedings of the 8th ECCOMAS Thematic Conference on MULTIBODY DYNAMICS 2017*, pp. 511-514, June 19 – 22, Prague, Czech republic, 2017.

[11] V. Hlaváček, "Design and Optimization of a Dynamic Vibration Absorber with Multiple Degrees of Freedom", master's thesis, CTU in Prague, 2017.