

Stiffness selection in synthesis of mechatronic discrete systems

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Abstract. In the paper, the known algorithm of designing of mechatronic discrete systems has been decomposed. As a result, detailed analysis of stiffness selection, during the process of distribution of dynamical characteristics functions, has been done. Based on synthesized one degree of freedom system that utilize piezostack actuator, detailed constraints related to the stiffness and their impact for mechanical, dimensionless and mechatronic parameters, have been investigated. The work extends the known problem of vibration control in discrete mechatronic systems

1. Introduction

Knowing the details related with stiffness selection, vibration isolation in mechatronic discrete systems, by use of synthesis method, can be deeply investigated and significantly improved. Utilization of piezo stack actuators for vibration control is well known [1]. Mathematical model of passive vibration with piezo transducers was shown in [2]. Different types of damping, respectively passive and active type in discrete mechatronic systems was confronted in [3].

Possibility to use negative value elements, in parallel with piezo has been introduced in [4], while using negative capacitance circuit [5]. Based on [4, 5] and works related with negative stiffness [6] authors introduced the problem of usage of negative elements in synthesis of mechatronic discrete systems [7].

The paper is verification and the continuation of Authors [1,3,7] works focused on stiffness selection. The work results in investigations related with stiffness impact for mechanical, dimensionless and mechatronic parameters in the mechatronic one degree of freedom cascade system. Based on the presented example, the paper leads to improvements in the efficiency of physical application of mechatronic systems, that can be easily synthesized and designed for given requirements in form of resonant and anti-resonant frequencies [7], in vibration control area.

2. Synthesis of mechatronic discrete systems

Synthesis of mechatronic systems is well known [1,3,7] and in case of cascade systems, is done based on dynamical characteristics function distribution into continuous fractions. The study on influence of main stiffness selections to all parameters has been done based on 1 degree of freedom (DOF) mechatronic structure, and in 2 DOF of system in mechanical replacement model. Two types of configurations have been in this case applied: *LC* and *LRC*, fig. 1.

The slowness function has been written as:



$$U(s) = H \frac{d_l s^l + d_{l-2} s^{l-2} + \dots + d_0}{c_k s^k + c_{k-2} s^{k-2} + \dots + c_1 s}, \quad (1)$$

where: l – odd degree of numerator, k – degree of denominator, $l-k=1$, H – any positive real number.

The dimensionless equation of presented in fig. 1. mechatronic structure in *LRC* configuration, and its mechanical replacement models is written as:

$$\begin{bmatrix} 1 & 0 \\ 0 & \lambda \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 2D_{LRC} \end{bmatrix} \begin{bmatrix} \dot{x}_1' \\ \dot{x}_2' \end{bmatrix} + \begin{bmatrix} 1+\gamma & -\gamma \\ -1 & 1+\delta \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (2)$$

where:

λ – nondimensional parameter which describes the relations of inertial elements,

γ, δ – nondimensional parameters which describes the stiffness elements,

$2D_{LRC}$ – dimensionless parameter which describes damping element.

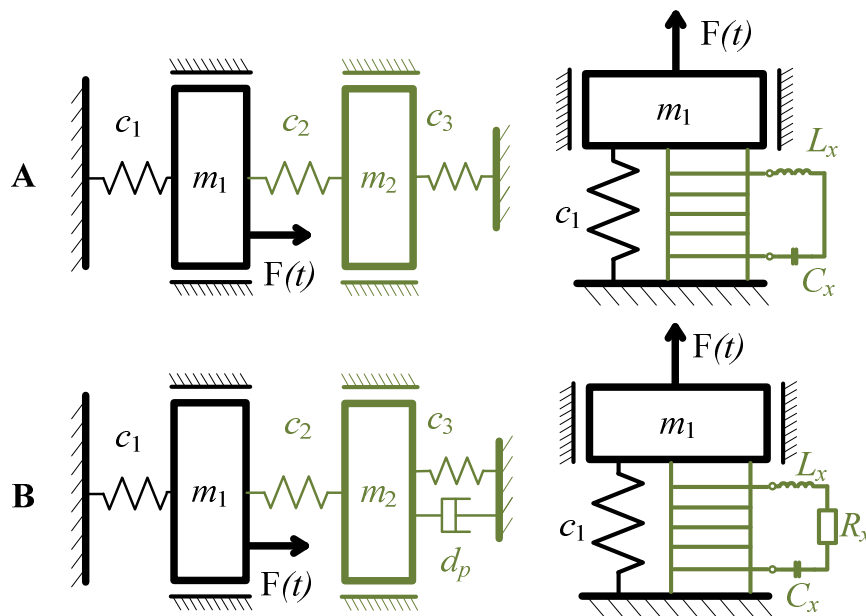


Figure 1. Mechatronic discrete systems in *LC* and *LRC* configuration and their replacement models

3. Mechanical parameters

Stiffness selection, in considered cases (c_1), is the first step to determine the structure of designed mechatronic systems. Normally it should be taken from required range:

$$\left(0, H \frac{d_0}{c_1} \right). \quad (3)$$

However it's possible to take it out of the range as well, causing negative value of the stiffness, and therefor impacting also on the other parameters in the system. This selection results in mechanical replacement model (fig. 1). The impact on inertial element m_2 and stiffness elements c_2 and c_3 are shown respectively in the fig. 2 and fig. 3.

For the visualization, requirements in form of poles and zeros have been set in the range of 1000 – 2500 Hz, and for this values following graphs are created.

The value of m_2 , is always positive and rapidly increases after taking the c_1 out of required range defined by the equation (2).

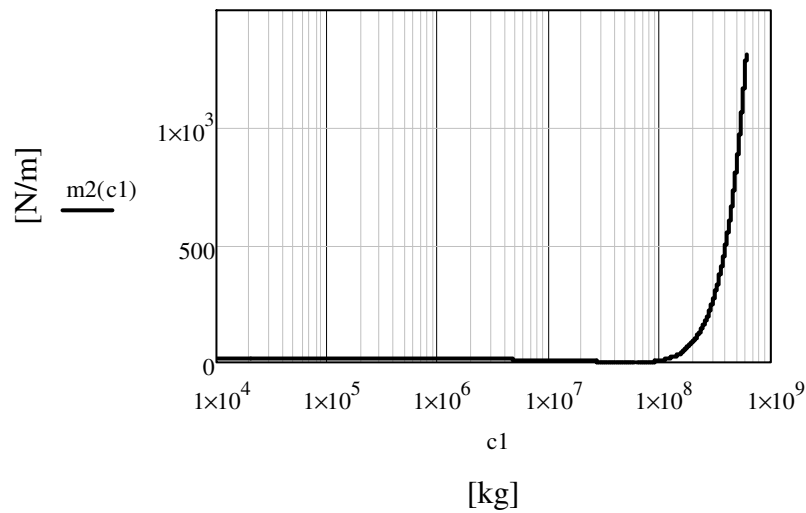


Figure 2. Influence of c_1 selection for m_2

Opposite to inertial element m_2 , stiffness elements might have negative value while taking the c_1 above required range. This cause also indirectly the impact on capacitance in external electric network that is connected to piezostack actuator. In this case, negative capacitance might be realized by the system described in [5].

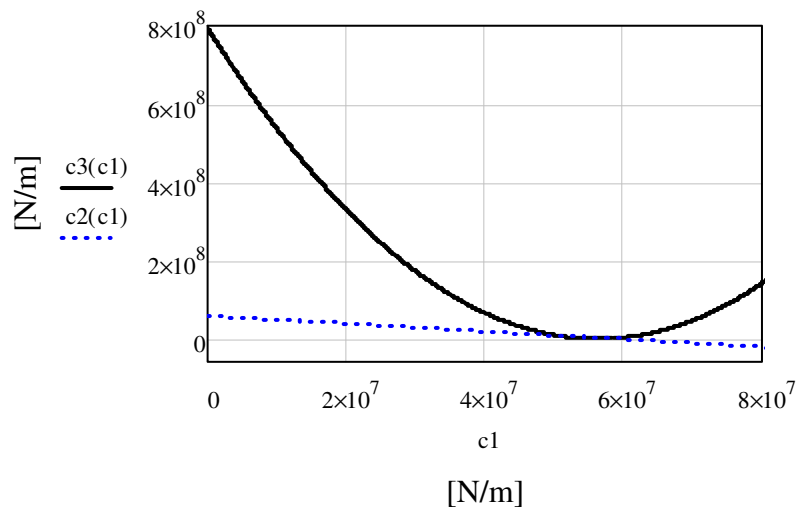


Figure 3. Influence of c_1 selection for remaining in the system stiffness elements c_2 and c_3

4. Dimensionless parameters

After reception of mechanical replacement model, during synthesis process, in next step this model is transformed to dimensional model, so the mechanical and electrical constrains related to piezoelectric effect and external electric network can be combined [7]. The system is analyzed in dimensional time:

$$\tau = \omega_m t, \quad (4)$$

where: ω_m - frequency connected with piezoelement position in the structure.

Influence for dimensionless inertial element is shown in fig. 4. The value of λ is positive, independently from selection of stiffness c_1 .

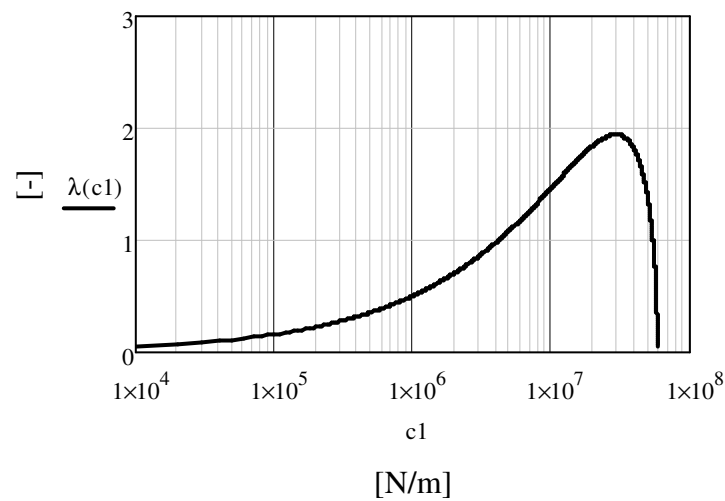


Figure 4. Influence of c_1 selection for parameter λ

In relation to given range (2) it's increasing until upper limit and then above defined ratio decrease. The impact c_1 for parameter γ is shown in fig. 5.

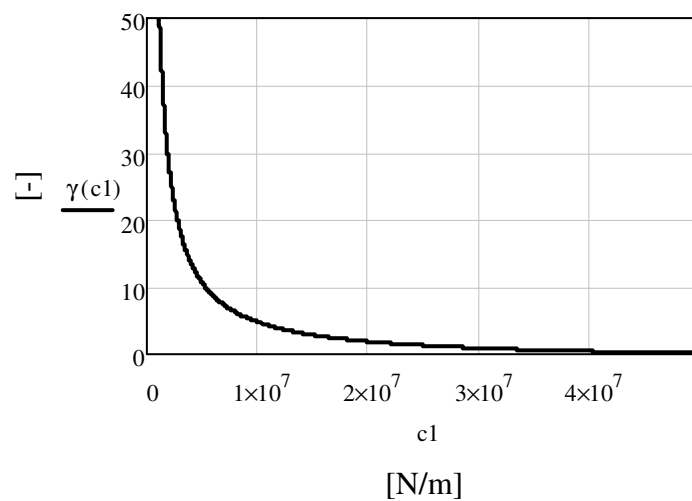


Figure 5. The impact of c_1 for parameter γ

Here selection from or out of the required range is neutral for the value. Similarly to parameter λ , γ which describe stiffness elements in mechanical replacement model is positive, but it's decreasing with increase of the value of c_1 .

5. Mechatronic parameters

Retransformation of dimensionless model to mechatronic structure is the last step in synthesis of considered discrete systems process [7]. Following the general piezoelectric equations it's possible to determine parameters of the piezostack actuator, and calculate the values of elements inside the external electric network.

To refer results of investigations to requirements which means to check how the requirements could also affect the values of considered parameters, three different resonant and antiresonant frequencies

has been evaluated (from range of 1000 – 2500 Hz). The bigger number in index of investigated parameter, the bigger value of pole and zero is applied.

The impact on selection of c_1 for capacitance in the external electric circuit is shown in fig. 6.

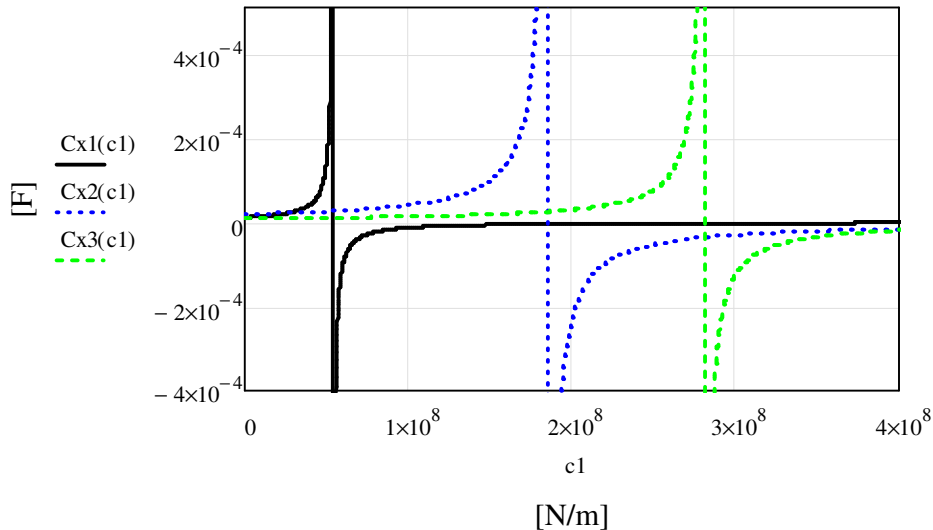


Figure 6. The impact of c_1 for capacitance C_x for different requirements

In all three cases, above the required range of selection of c_1 , the value of capacitance in external electric network is negative. The influence of considered stiffness for resistance in electric circuit is shown in fig 7.

In this case, with increase of c_1 , the resistance is also increasing. Another parameter that is affecting resistance in electric circuit is selection of parameter d_p , which is in this case proportional to stiffness c_3 and was described inter alia in [7].

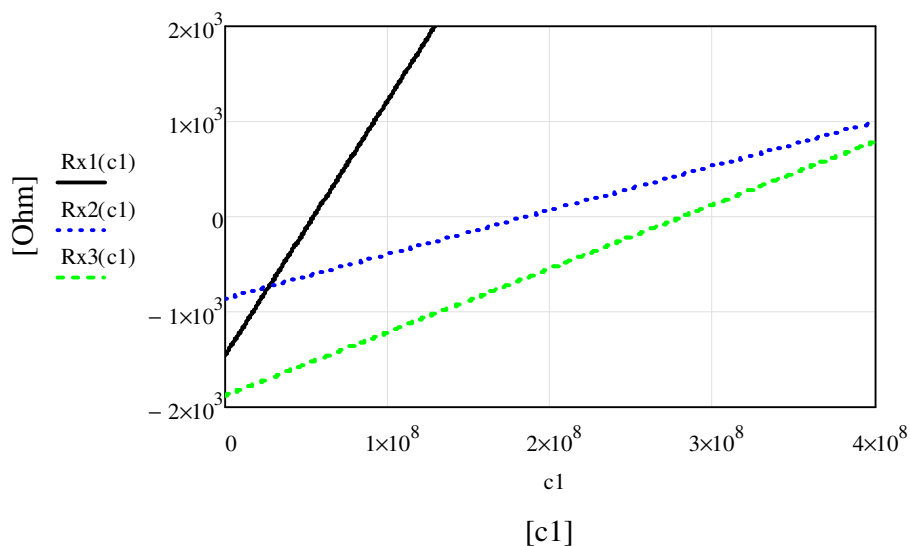


Figure 7. Influence of c_1 selection for resistance in external electric network R_x studied for different requirements

Finally, the impact of selection of c_1 for inductance in the final mechatronic system, is shown in fig. 8. Opposite to capacitance and resistance, inductance is decreasing with the increase of c_1 .

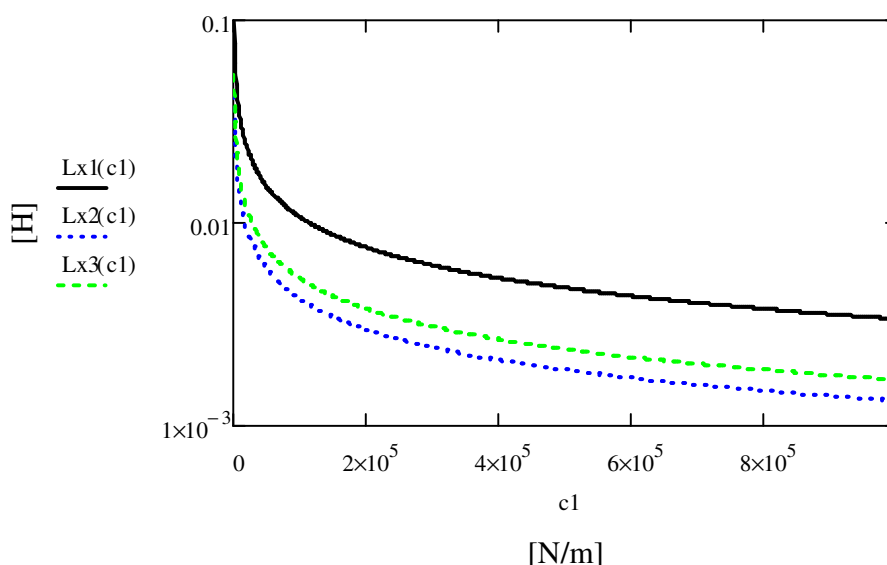


Figure 8. The impact of c_1 for inductance L_x for different requirements

6. Summary

In the paper, study on selection of stiffness elements, which is the key point during synthesis process, has been done. Based on example of cascade system with 1 DOF in mechatronic system, investigations related for verification of the impact for mechanical, dimensionless and mechatronic parameters of the system has been shown. Following the results and presented graphs, increase of the value of c_1 decrease the value of inductance and increase the value of R_x and C_x . Over the upper limit for c_1 selection, described by (3), C_x gets negative value, which is then also increasing with the increase of the value of the stiffness c_1 .

It's also possible to select stiffness to obtain different damping functions of the systems: passive damping, where all parameters has positive values and contains passive elements (L_x , R_x), and adaptive-passive (C_x). That leads to negative values of capacitance or resistance elements which are another options for vibration elimination in considered systems that must comply with given requirements in form or resonant and anti-resonant frequencies.

Additionally, detailed graphs related to major constrains have been presented for the extension of possible applications of considered systems in vibration control as dampers that have been built from piezostack actuator and connected LRC network with/without negative values elements. Potential applications of the systems can be found in the areas of micro-positioning, optics elements and precise devices.

In further research works, detailed study on stability conditions and physical realization related to available in the market piezoceramic elements and their parameters like piezoelectric capacitance will be studied and constrained.

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