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ANALYSIS AND DESIGN OF COMBINED ELECTRONIC AND MICRO - MECHANICAL SYSTEM THROUGH MODELLING AND SIMULATION

[1]M. Atanasijević-Kunc, [1]V. Kunc, [2]J. Diaci, [1]J. Trontelj, [1]R. Karba

[1]Faculty for Electrical Engineering, Ljubljana, Slovenia
[2]Faculty of Mechanical Engineering, Ljubljana, Slovenia

Key words: micro-mechanical systems, smart sensors, modelling, simulation, control design

Abstract: In the paper an integrated micro-mechanical acceleration sensor is described through several stages, where open and closed loop dynamical properties are studied by modelling, simulation and animation in comparison with measurement data. The accurate and reliable model is not important only for realization of the system, but can be used also for development of the new generation of similar systems and for optimization of the existing devices. In this way a number of costly iterations of micro-mechanical prototypes can be greatly reduced and the design time and effort minimized.

Analiza in načrtovanje kombiniranega elektronskega in mikro-mehanskega sistema s pomočjo modeliranja in simulacije

Ključne besede: mikro-mehanični sistemi, pametni senzorji, modeliranje, simulacija, načrtovanje vodenja

Izvleček: V prispevku smo predstavili nekatere dinamične lastnosti mikro-mehaničnega sistema, ki deluje kot senzor pospeška. Omenjene lastnosti smo proučevali v večih korakih s pomočjo modeliranja, simulacije in animacije in sicer v primeru, ko sistem deluje kot odprtozančen, pa tudi pri realizaciji povratnozančnega vodenja. Rezultate modeliranja smo ovrednotili v primerjavi z meritvami na realnem sistemu. Tovrstni rezultati so pomembni tako v fazi samega načrtovanja sistema, pri optimiranju delovanja, uporabni pa so tudi za študij načrtovanja novih generacij podobnih sistemov, kar vse lahko pripomore k zmanjšanju stroškov in časa realizacije.

1. Introduction

Integrated micro-mechanical sensors are ideal for volume production of accurate, cheap and extremely small sensors for different physical quantities such as pressure, acceleration, rotation speed and many others. They comprise two main parts. The first part is the micro-mechanical device, which can be a self-standing element (in a joint package with the electronic) or an integrated element. The integrated micro- mechanical element as in our case is done during post-processing of the silicon wafer using technological procedures similar to the one used in microelectronic production. This usually limits the choice of material to silicon and silicon oxide and the geometry of the mechanical device is predominately two-dimensional realized using a limited number of stacked layers.

The second part is the electronic system. It is realized using standard micro-electronic production techniques and interacts with the mechanical part using capacitive position sensing principles that means it influences the mechanical part with electrostatic force.

To successfully join both parts into a measurement system the task of modelling the complete system is of vital importance. The stem level model must comprise the model of electronic part, the model of mechanical part and all the interactions between the two. In case of closed loop sensor realization also the controller functions must be integrated for correct dynamic interpretation.

2. System description

The mechanical part of the measurement system is realized as a poly-silicon cantilever, which is 490μm long, 211 μm wide and 0.9μm thick. On one side it is attached to the bulk silicon and the other side is free to move. The mechanical part is placed above the electronic part as is schematically presented in Fig. 1.

The electronic part comprises three electrodes made by top metalization layer forming a capacitance to the beam. The beam is electrically connected to the ground potential of the electronic system since such solution is most favorable from the mechanical point of view. So the electrodes of the electrical part are forming capacitors with the cantilever as a grounded electrodes. They are used to form distance measurement capacitors. In combination with extremely sensitive capacitance measurement electronic integrated in the electronic part these electrodes precisely detect the distance of the mechanical part to the sensing

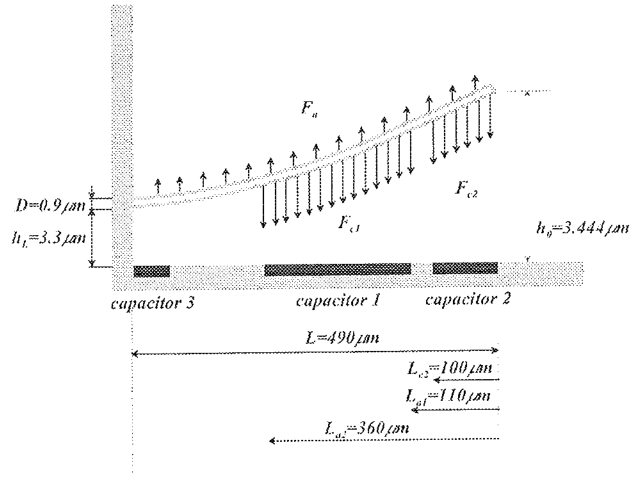

Fig. 1. Schematic system representation

electrodes. The electrode beneath the beam tip and the electrode in the middle of the beam are also used to exert electrostatic force to attract the beam (the actuation force).The third capacitor is used only to detect the starting beam distance from the silicon surface.

The described measurement system can operate in two modes, the open loop and closed loop mode. In the open loop mode the feedback part of the system is disabled and the electronic is only used to monitor the cantilever position and for testing the dynamic properties of the system itself. When the system is subjected to acceleration the corresponding force displaces the beam. The displacement magnitude is dependant on the beam stiffness and the dynamic is governed by the air damping. The displacement is detected by the beam position sensing electronic and conveyed to the system output.

Functional system properties can be significantly improved by the realization of the close loop. In this case the electrostatic actuation force counters the acceleration induced beam displacement. The resulting displacement is so much smaller and is dependant on the closed loop gain. The measure of the acceleration is in this case the amount of the actuation force applied. It is clear that such system is far more linear than the open loop one and its frequency behavior can be influenced by the closed loop gain.

3. System modelling

The model construction was done in two main phases. The first started during the initial stage of the project to help the design of the first prototypes of the measurement system. The construction of this initial model based on the theoretical model of the mechanical part of the system and on the results of the simulation of the electrical part, which was realized by SPICE simulator /1/.

After receiving the first prototypes of the micro-mechanical system a detailed evaluation phase followed. During this a number of measurement data enabled further model improvement. This enhanced model will serve for further system development and optimization.

The theoretical model is governed by the equilibrium of all the forces in the system. They can be described from the mechanical and electrical point of view.

It is obvious that for the mechanical part partial differential equations can be used for displacement description. Since our wish was the description of the system in time domain for simulation and animation purposes we decided to use for the mechanical part the finite element differential description /2/. For this the beam was divided into twenty segments each consisting of mass, spring and damping element, as is illustrated in Fig. 2. It seems that this number is a good compromise between the simulation accuracy and simulation time. Boundary conditions were satisfied from displacement and rotation angle calculations.

Here it is important to point out that damping is in our case highly nonlinear function of deflection and is heavily dependant on the air gap between the cantilever and the silicon surface. This can be explained by the fact that the distance between the silicon and the cantilever beam is extremely small. The consequence is that the air in the gap can not freely move /3,8/. So adapted air damping model was used as is described with the following equation:

$$f_i = \frac{\nu B^3 L \alpha\ (B/L)}{y_i^4} \tag{1}$$

where f_i denotes the damping of the i-th element, y_i is the distance of the i-th element from the surface, L and B are the length and width of the beam, n is viscosity and α is geometry dependant constant.

Model describing mechanical part has therefore 40-states (2 for each element) and is highly nonlinear.

As mentioned the cantilever beam is placed above the measurement electronic consisting of two main capacitor plates forming the capacitance to the beam as is illustrated in Fig. 3. Electrostatic force of each element of the corresponding capacitor to the corresponding part of the beam can be described with the following equation:

$$F_{ci} = \frac{1}{2} \varepsilon A_i \left(\frac{U_{in}}{y_i} \right)^2 \tag{2}$$

where ε is dielectric constant, A_i is the area of the i-th part of the capacitor and U_{in} is applied input voltage. It must be taken into account that the applied voltage on both capacitors was in open loop mode only up to 50% of the time due to the multiplexing of measurement and actuation. So for open loop purposes the equation (2) was replaced with:

$$F_{ci} = \frac{1}{8} \varepsilon A_i \left(\frac{U_{in}}{y_i} \right)^2 \tag{3}$$

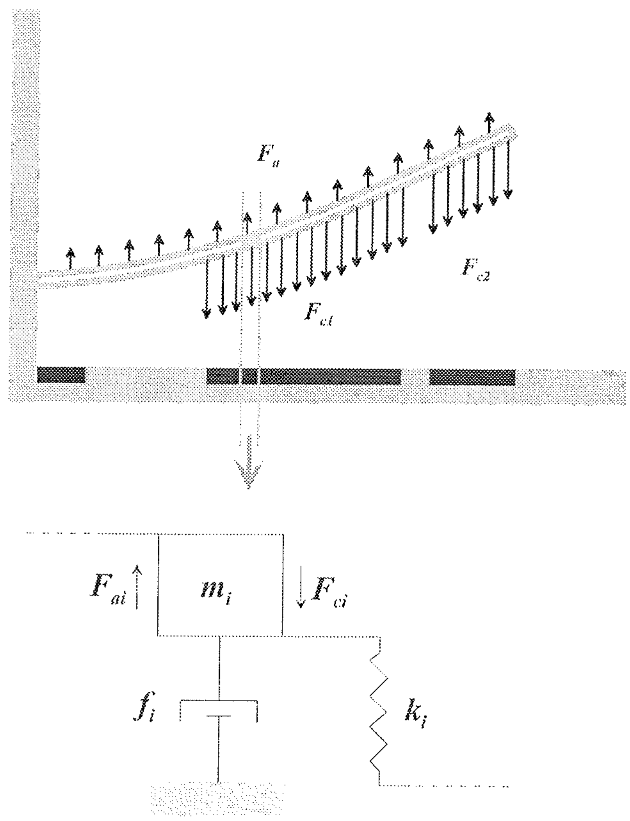

Fig. 2. Modelling of the mechanical part

as in our case only 25% of the time period was used for actuation purposes.

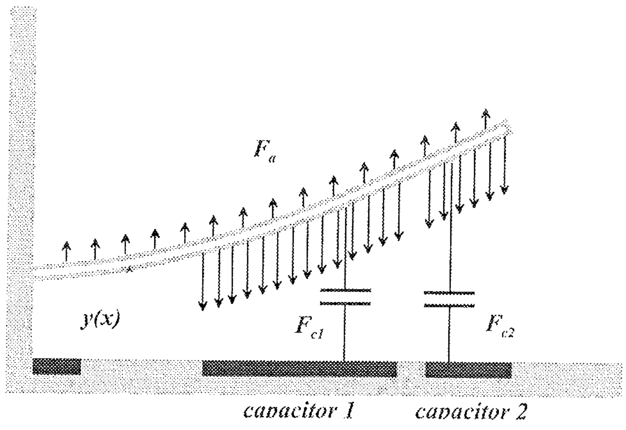

Fig. 3. Modelling of the electrical part

Deflection measurement property can be for each capacitor segment described with:

$$U_{ci} = K_{1i} \frac{1}{K_{2i} + K_{3i} \dfrac{1}{y_i}} \tag{4}$$

where K_i are adjustable constants of electronic measurement system. In our case for measurement purposes only capacitor 1 was used and the output voltage was evaluated as the average value of all segments above the capacitor plate:

$$U_{out} = \frac{1}{n_j} \sum_{j=1}^{n_j} U_{cj} \tag{5}$$

In the second phase of model construction the actual data gathered during the evaluation phase of the first prototypes was introduced to adjust the model parameters. The measurement results were divided into a static and dynamic data. The static data consisted of initial distance of the beam tip and core from the surface electrodes and the value of the capacitance at the beam tip. Also the static characteristic of the beam tip deflection as a function of actuation voltage was presented.

Data from a number of devices were entered as input data to the model simulation and were used to adapt the model. Once this was done and a reasonable matching between the simulation and measurement results was obtained the more demanding task of dynamic system model adjusting could begin.

The measurements of dynamic behavior of the prototype samples were done in both possible modes of operation. The open loop measurements consisted of time domain observation of the cantilever tip displacement resulting from step function changes in actuation voltage. The digital oscilloscope was used to track the beam tip movement as measured by the distance sensing electronic. System and model responses for different step changes are illustrated in Figs. 4 to 6. In all figures input voltage is presented first and followed by the beam tip displacement. In the third part measurement data are compared with model responses. All simulation results were obtained using Matlab/Simulink program environment /4,7/.

From this it is possible to conclude that good open loop matching was obtained in different voltage ranges.

The closed loop measurements used the externally adjustable reference voltage as the input stimulus. This reference voltage is used in the normal system operation to position the beam tip at the required distance from the sensing electrode. The step-wise change of the reference voltage thus meant that the close loop system must change the actuation force to move the beam tip into the newly required position. The movement of cantilever tip was again monitored using a digital oscilloscope. Efficacy of the closed loop operation is illustrated in Fig. 7 where error signal is compared for the model response and measurement data.

4. Conclusion

In the paper modelling and simulation results are presented and compared with measurement data for the integrated micro-mechanical acceleration sensor. Presented work

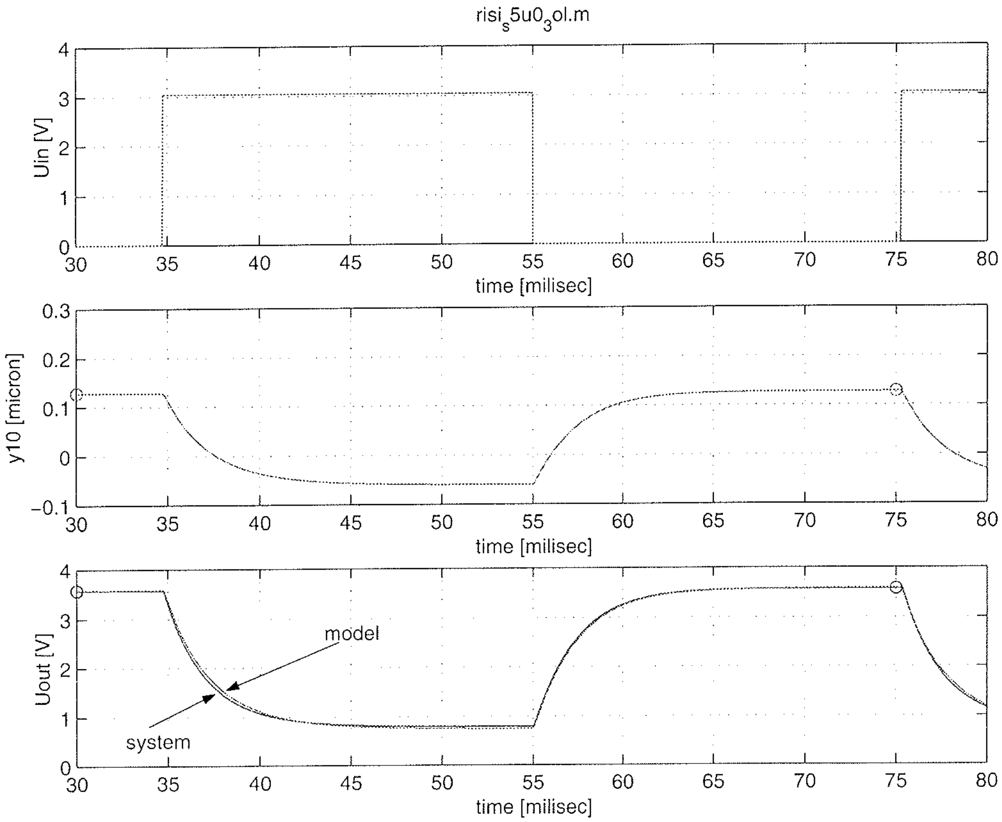

Fig. 4. Open loop system responses in comparison with measurement data (input voltage changes form 0 to 3 V)

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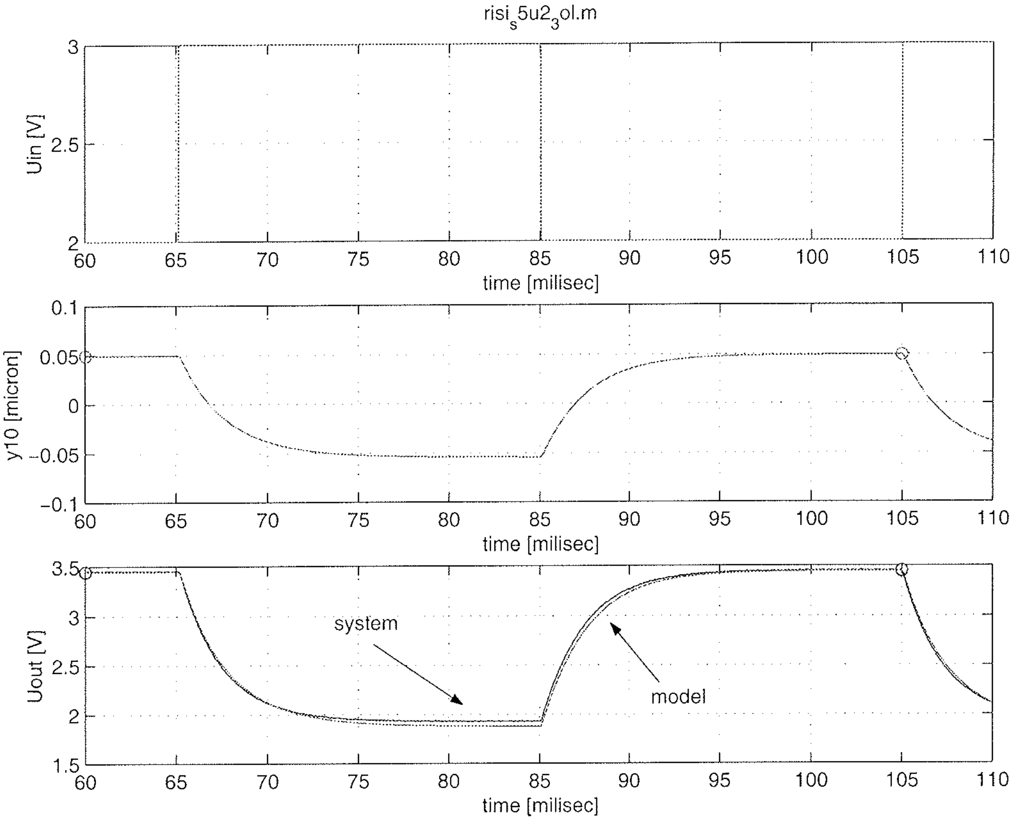

Fig. 5. Open loop system responses in comparison with measurement data (input voltage changes form 2 to 3 V)

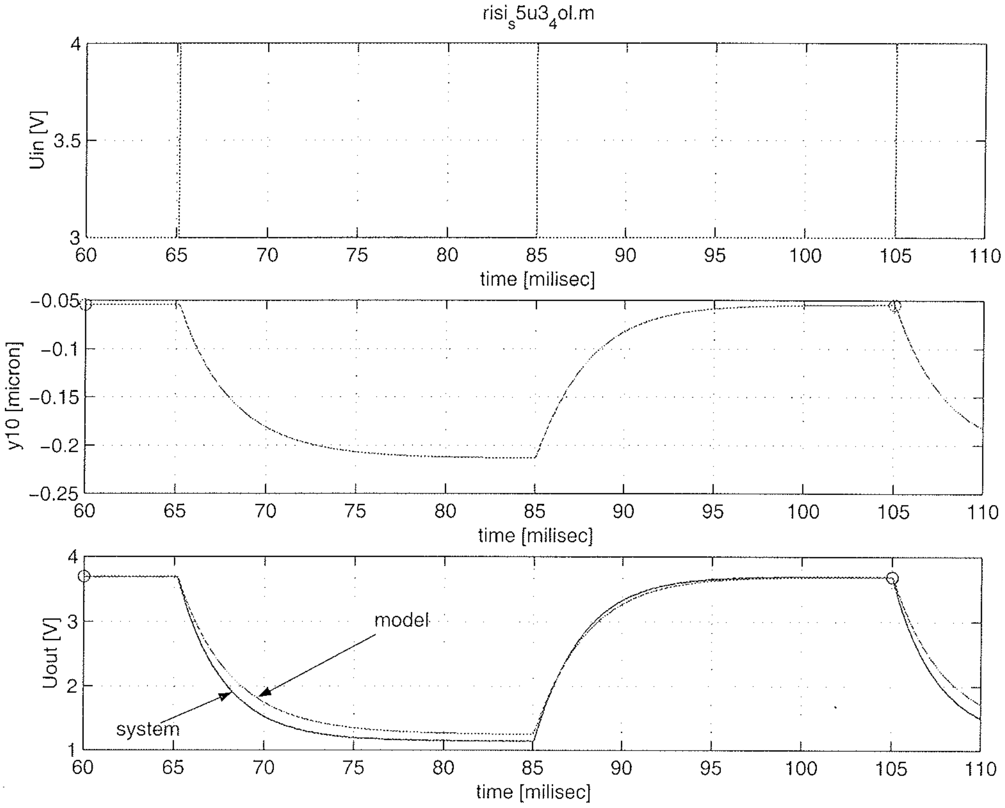

Fig. 6. Open loop system responses in comparison with measurement data (input voltage changes form 3 to 4 V)

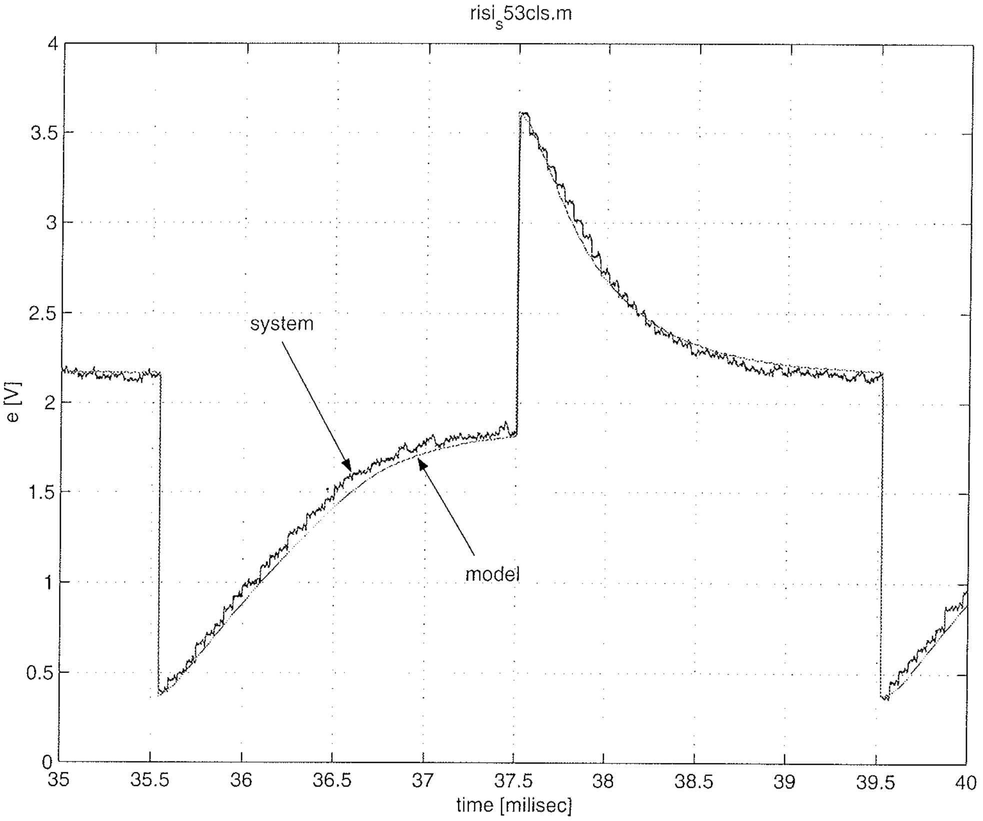

Fig. 7. Closed loop system response – error function - in comparison with measurement data

The starting model was based on theoretical equations and was further improved using measurement data taken from prototype devices. The model development was done in two major steps. The first step covered the static characteristic of the system resulting from the equilibrium of the electrical actuation force and cantilever spring force. The second step was the introduction of dynamic properties governed mainly by air damping mechanisms. When acceptable matching of open loop responses was obtained the model was tested also in the closed loop where the main controller functions are the adaptation of frequency range which can be satisfied by suitable chosen gain and of course linearization effect, needed because of highly nonlinear system properties.

The final results seems to have a high degree of compliance to the actual measurements and will be used for further optimization of the system, saving a lot of extremely costly experiments.

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Asst. Prof. Dr. Maja Atanasijević-Kunc
e-mail: maja.atanasijevic@fe.uni-lj.si
Tel.: +386 (01) 4768 314

Dr. Vinko Kunc
e-mail: vinko@kalvarija.fe.uni-lj.si
Tel.: +386 (01) 4768 337

Prof. Dr. Janez Trontelj
e-mail: janez@kalvarija.fe.uni-lj.si
Tel.: +386 (01) 4768 333

Prof. Dr. Rihard Karba
e-mail: rihard.karba@fe.uni-lj.si
Tel.: +386 (01) 4768 251

Faculty for Electrical Engineering
Tržaška 25, Ljubljana, Slovenia

Asst. Prof. Dr. Janez Diaci
Faculty of Mechanical Engineering,
Aškrčeva 25, Ljubljana, Slovenia
e-mail: janez.diaci@fs.uni-lj.si
Tel.: +386 (01) 4771 615

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