TECHNISCHE UNIVERSITÄT
ILMENAU

50. Internationales Wissenschaftliches Kolloquium

September, 19-23, 2005

Maschinenbau von Makro bis Nano / Mechanical Engineering from Macro to Nano

Proceedings

Fakultät für Maschinenbau /
Faculty of Mechanical Engineering

Impressum

Herausgeber:	Der Rektor der Technischen Universität Ilmenau Univ.-Prof. Dr. rer. nat. habil. Peter Scharff
Redaktion:	Referat Marketing und Studentische Angelegenheiten Andrea Schneider
	Fakultät für Maschinenbau Univ.-Prof. Dr.-Ing. habil. Peter Kurtz, Univ.-Prof. Dipl.-Ing. Dr. med. (habil.) Hartmut Witte, Univ.-Prof. Dr.-Ing. habil. Gerhard Linß, Dr.-Ing. Beate Schlütter, Dipl.-Biol. Danja Voges, Dipl.-Ing. Jörg Mämpel, Dipl.-Ing. Susanne Töpfer, Dipl.-Ing. Silke Stauche
Redaktionsschluss: (CD-Rom-Ausgabe)	31. August 2005
Technische Realisierung: (CD-Rom-Ausgabe)	Institut für Medientechnik an der TU Ilmenau Dipl.-Ing. Christian Weigel Dipl.-Ing. Helge Drumm Dipl.-Ing. Marco Albrecht
Technische Realisierung: (Online-Ausgabe)	Universitätsbibliothek Ilmenau ilmedia Postfach 10 05 65 98684 Ilmenau
Verlag:	isle Verlag ISLE, Betriebsstätte des ISLE e.V. Werner-von-Siemens-Str. 16 98693 Ilmenau

ISBN (Druckausgabe):	3-932633-98-9	(978-3-932633-98-0)
ISBN (CD-Rom-Ausgabe):	3-932633-99-7	(978-3-932633-99-7)

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=15745

50. Internationales Wissenschaftliches Kolloquium
Techniche Universität Ilmenau
19.-23. September 2005

L. Valenta / A. Huba / I. Muka

Silicone Rubber Strain Gauge with High Elasticity

ABSTRACT

The application of silicone elastomeres can not be compared by this of traditional materials. Their industrial production goes back only to the 40's and 50's. Their "carrier" nowadays is however spectacular in each industry branches [1] including the mechanical engineering and in the food industry. In some fields they are not to replace like in medical applications. The paper summarise the results of the investigations at the BME and presents special silicone composites in new applications as hyperelastic sensor (patented) giving new ideas for constructers in the innovation process.

INTRODUCTON

New perspectives are opened for the manufacturing of products of the precision engineering and of the medical instrumentation by the special mechanical, electrical, optical, biochemical etc. properties of the "family" of silicone elastomeres. Our department concerns since some years with the application of these materials in different constructions. At the beginning of our investigations only few of the important material parameters for the FEM simulations and only partially information in wide range were given. Material models were known only in general form for elastomeres. So first it was unavoidable to estimate the exact material characteristics and material models. Since other essential material parameters like storage modulus and loss modulus depend on temperature and frequency FEM simulations and design of dynamic systems claim exact knowledge of these characteristics.

DYNAMIC BEHAVIOUR OF THE SILICONE RUBBER MATERIAL

One of the application fields of the sensor-actuator silicon rubber could be even the mechatronics. Mechatronic systems works always dynamical, the knowledge of exact dynamic and electric properties of the applied silicone material is necessary. Silicon-rubbers as special polymers have strong non-linear material parameters (relaxation and creep). In case of the dynamic simulations of the silicon rubber constructions with programs like MARC or ANSYS to decrease the errors it is important to use the exact material law obtained by the measuring on numerous test objects. The application of silicon rubber as ***construction material*** is not yet obvious. In cooperation with the

TU Ilmenau our research group tries to combine this material with metals, silicone and with other polymers to create new flexible structures [2].

A. Material modelling

For the identification of the dynamic model of this material we suggested a new method in the material science. This is the method of ***synthesis*** well known for the calculation of passive electric filter networks. The system ***analysis*** is used for a long time for the description of the dynamic properties of materials and also for polymers usually the "black-box" method is applied however the synthesis method for creating the network model of the material was not used. From the results of the one-axis strain-stress relation one can conclude to the dynamic model of the material. It means that if the input and output signals are given the unknown linear system can be determined but this process was empiric.

In case of silicone rubber the problem is that no one of the conventional dynamic models (Kelvin, Maxwell, Voigt, Standard Solid, Burgers) can describe exactly its properties. We looked for the common dynamical model for both of strain and relaxation process. Our model with lumped but non-linear parameter describes with minimal error the dynamic behaviour of the investigated materials. The result of a large number of tests with silicone rubber probes is presented in [3] and [4].

B. Model identification by synthesis method

It is known that for linear systems (in time and in operator domain as well) it is possible to determine the unknown third function if two of three are given. In this case the exciting input time function and the system time response - the measured values of strain and stress (force) - are known. We obtain the best passive network for the actual transfer function using the synthesis method by mathematical operations and not by empiric approximation. Problems can occur - and we had to confront with those also - that no every transfer function corresponds with a real network but there is a solution in form of approximated roots.

The standard input function with the start time $t\left(0^{+}\right)$ is whether ***the unit velocity function*** (strain) or the ***step function*** (deformation velocity) with *v(t)= 50 [mm/min]* .

Wacker manufactured silicon rubber types have been analysed. (R 4105/40-60-80 IGET). The hardness of these could be sorted into three groups: Sh40, Sh60, Sh80.

The average values of the system answer functions ***σ(t)*** and ***f(t)*** have been approximated and also their Laplace transforms were calculated with help of the program “Mathematica 3.0”.

C. From stress analysis to admittance network

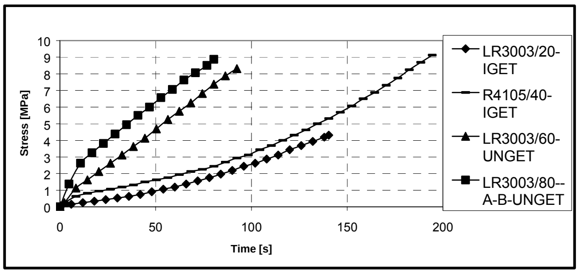


Fig. 1. Typical strain-stress diagrams of the analysed silicon rubbers

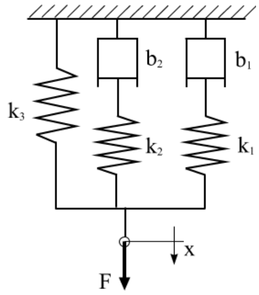


Fig.2. One of the dynamic models of the analysed rubber types

Regarding that

$$L\{v(t)\} = \frac{v_0}{s} = V(s) \qquad \text{we obtain} \qquad Y(s) = \frac{\sigma(s)}{V(s)} = L\{\sigma(t)\} \cdot \frac{s}{v_0} \tag{1}$$

The transfer function represents in our case ***Z(s)*** or ***G(s).***

$$G(s) = \frac{F(s)}{V(s)} = \frac{A_0 \sigma(s)}{V(s)}. \tag{2}$$

Substituting the Laplace transforms of σ(t) and v(t) we obtain the following transfer function considered for resulting admittance.

$$G(s) = \frac{A_0}{v_0} \cdot \frac{\beta_0 + \beta_1 s + \beta_2 s^2}{s(\sigma_0 + s)(\sigma_1 + s)} \tag{3}$$

The function can be written in fractal form for identifying the corresponding admittance network but there are some equal variants for this. One of them is shown in the Fig. 2.

$$G(s) = \frac{A}{s} + \frac{B}{s+\sigma_0} + \frac{C}{s+\sigma_1} = \frac{k_3}{s} + \frac{1}{\frac{s}{k_2} + \frac{1}{b_2}} + \frac{1}{\frac{s}{k_1} + \frac{1}{b_1}} \tag{4}$$

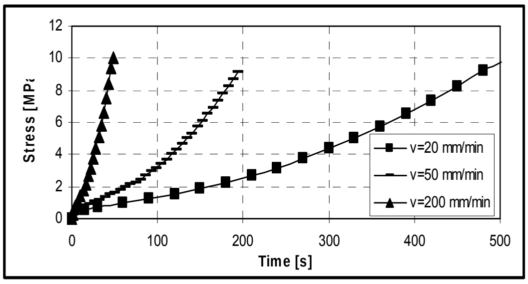


Fig. 3. The strain-stress characteristic depends on the strain velocity

The calculated network consists 5 parameters (k_1, k_2, k_3, b_1, b_2), exactly two parallel Maxwell-models parallel with a spring.

D. Non-linear dynamic material model

The mechanic behaviour of polymers are usually non-linear - silicon rubbers are also not exceptions. They have *long, winded chain structure*. In Fig. 3 one can follow how the stress changes depending on the different strain velocity [6], [8]**.** The diagrams in Fig. 4 and 5 show that the stiffness depends on the measure of the elongation and the damping factor depends on the deformation velocity.

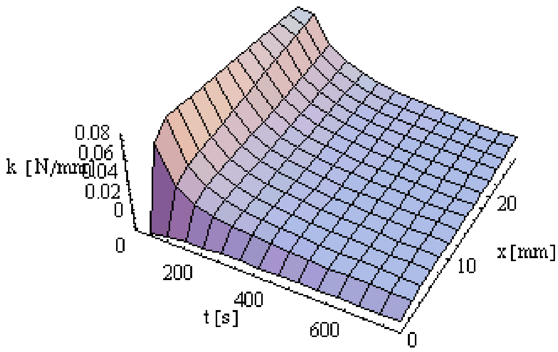


Fig. 4. The stiffness depending on the strain and the time (relaxation process)

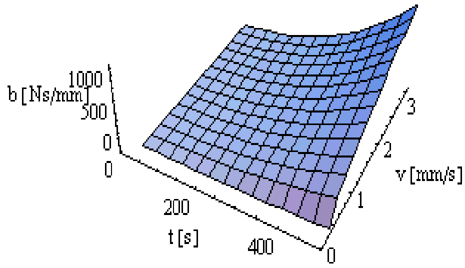
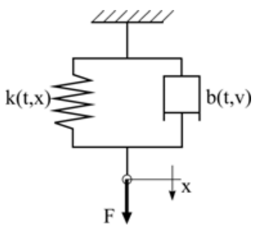


Fig.5. Damping depending on the velocity and time (creep)

In reality the stiffness depends mainly on the average chain length and on the type of radicals and this is supported by the measuring.

SILICONE RUBBER AS STRAIN GAUGE

Wackers made soot dotted silicon rubber type R570/70 have been analysed to clear the relation between strain and electric resistance. Commercial strain gauges made from semiconductor material or from metal work only in the range of $10^{-7}\langle \varepsilon = \frac{dl}{l} \langle \approx 10^{-3}$. Conductive silicon rubber could offer a technical solution for deformation measuring of high elasticity structures made from polymers especially from silicon rubber.



$$F(t) = k(t,x) \cdot x(t) + b(t,v) \cdot v(t)$$

Fig. 6. The nonlinear model of the silicon rubber

The idea is patented in [7]. The results of the investigation show that there is a significant correlation between strain and conductivity and this effect is reproducible. Change rates up to 250 – 300 % related to the base resistance could be achieved although the characteristic is non-linear. The conductive silicon rubber can be applied in the recent form for example as limit switch. The investigation is going on to develop materials with better linearity for the use as analogue sensor.
The electric properties of the carbon dotted polymers are determined by the type, amount and the size of particles [5]. In our sensor the carbon particles are statistically spread in the filling silicone rubber material and they are in connection since the average distance of them is about 100 Å or less. There are two main electric resistances to observe. The resistance of the carbon particles R_A and the complex impedance of the contact surfaces $Z_C(s) = R_C \| sC_C = \frac{R_C}{sR_C C_C + 1}$. Our measuring results show that the resulting resistance really decreases for higher frequencies. The next figure shows the simple model of the conductive silicone rubber gauge.

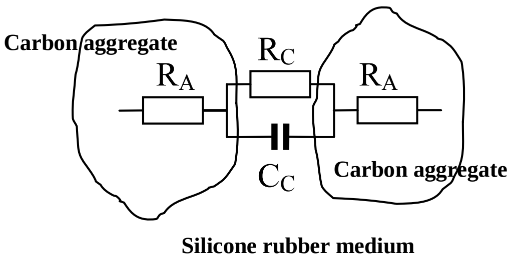
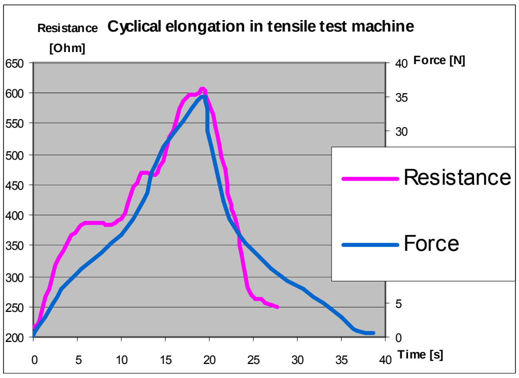


Fig. 7. The simple structure model of conductive silicone rubber

The doting by carbon makes the silicon rubber electrically conductive. Adding 10-30 nm sized acetate carbon into the rough material of the silicon rubber, after the vulcanization electrically conductive rubber is given for use. The higher the amount of carbon in the composite, the higher is also the conductance of it. The answer function of elongation is continuously, so the rubber conducts the electricity by tunnel conductance, not by contact conductance. The percentage of carbon influences however strongly the mechanical properties of the material.
The electrically conductive silicon rubber can be applied as sensor in a wide range of deformation but also other special properties can also be useful. Such properties are the easy and safety manufacturing, the large range of thermal usage, the excellent environmental resistance like the hard water-repellent.

In the next figures we present some measuring results supporting the correlation between the force on the silicone rubber strip and the changing of resistance in the low frequency range. We also show the fatigue elongation and bending test results.



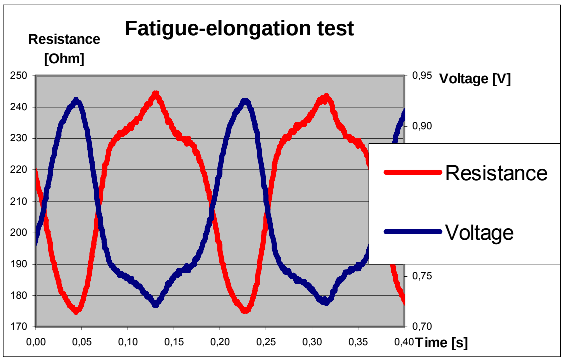
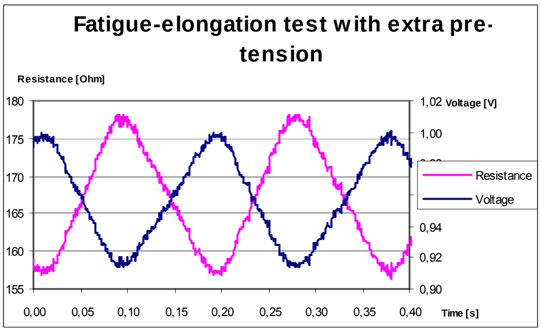


Fig. 8. Measured relation of electric and mechanical behaviours of conductive silicon rubber

Fig.9. Periodic elongation test of conductive silicone rubber without pretension

Fig. 8 shows that the resistance changing rate allows the application not only in Wheatstone-bridges but also in direct measuring method.

For dynamic systems cyclic bending fatigue tests and axial loading cyclic stress fatigue tests were also claimed.



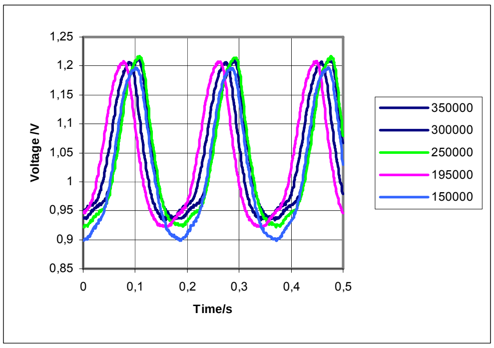


Fig. 10. Periodic elongation after pretension

Fig. 11. Cyclic fatigue-test for bending

The aim of tests is not only to determine the life span but also to know if the conductivity changes according to the cyclic mechanical load.

Fig. 9 shows in case of bending that the resistance stays stable during the load changes. It is important that the shape of the load curve does not change even after 350.000 load changes only the average value is shifted. The measuring information is carried by the curves depending on the mechanical load. Pre-stress of the silicon rubber improves the linearity and cyclic preloading is necessary to stabilize the electric material properties see Fig. 8.

APPLICATION ON PNEUMATIC MUSCLE

The actuator is a so called Pneumatic Muscle manufactured by FESTO, which was introduced a few years ago. We placed for the measuring of displacement a carbon doted silicon rubber stripe as sensor on it with the goal to realize the position control of the high elasticity actuator.

The contracting pneumatic cylinder – called as pneumatic muscle – works like the real muscle. That is a type of membrane contracting cylinder which has two main elements. One of them is a tube which is made of a relatively soft, leak-free gasket material. The other is a net which contains fibers in rhomboid shape. These fibers do not change their geometry. The net gives the strength to the cylinder and wears the mechanical stress. In the cylinder – like in every cylindrical body – radial and axial forces rise due to the inertial pressure.

In the case of the Pneumatic Muscle the net structure is designed to carry all the forces. When the system gets to be under pressure the shape of the net changes, the length of the tube will be smaller and the diameter will be larger, and the tube will produce an axial pulling force. This pulling force can be affected by the pressure.

The change of shape is rather large. Normal gauge with a strain range of $10^{-7} \leq \varepsilon \leq 10^{-3}$ can not be applied for measuring of the length changing of the Pneumatic Muscle so we use the advantages of our silicone rubber gauge. The resistance changing due to the pulling force is measured.

After the digitalization of the measured voltage – dependent to the resistance of the rubber – a digital proportional control is realized by a microcontroller. The microcontroller controls the applied pressure by an electromechanical valve. The Pneumatic Muscle is initially loaded by a known weight, and there is a possibility to set up a reference value – independently to the stress relaxation – by a helical potentiometer Fig. 12.

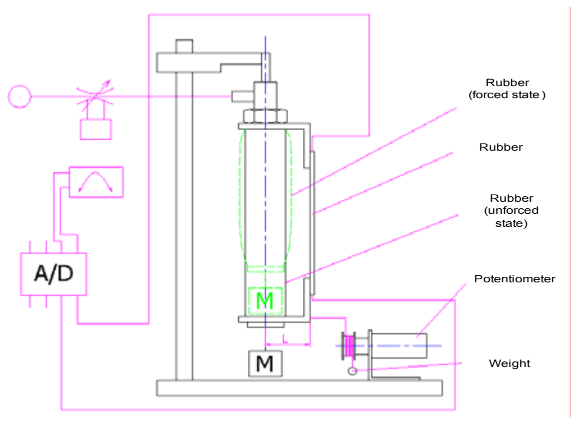


Fig. 12. Arrangement of the control system for Pneumatic Muscle

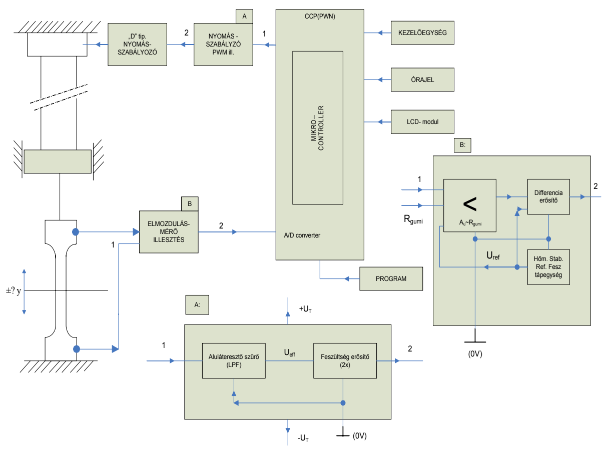


Fig. 13. Block diagram of the control

The signals of the transducer reach the microcontroller through the interface unit. The output signal of the microcontroller is a PWM sign, which is filtered by a low pass filter and amplified for driving of the electric valve. The desired position value of the actuator can be set up on a BCD switch.
Fig. 13 shows the block diagram of the control of Pneumatic Muscle and Fig. 14 illustrates the test equipment.

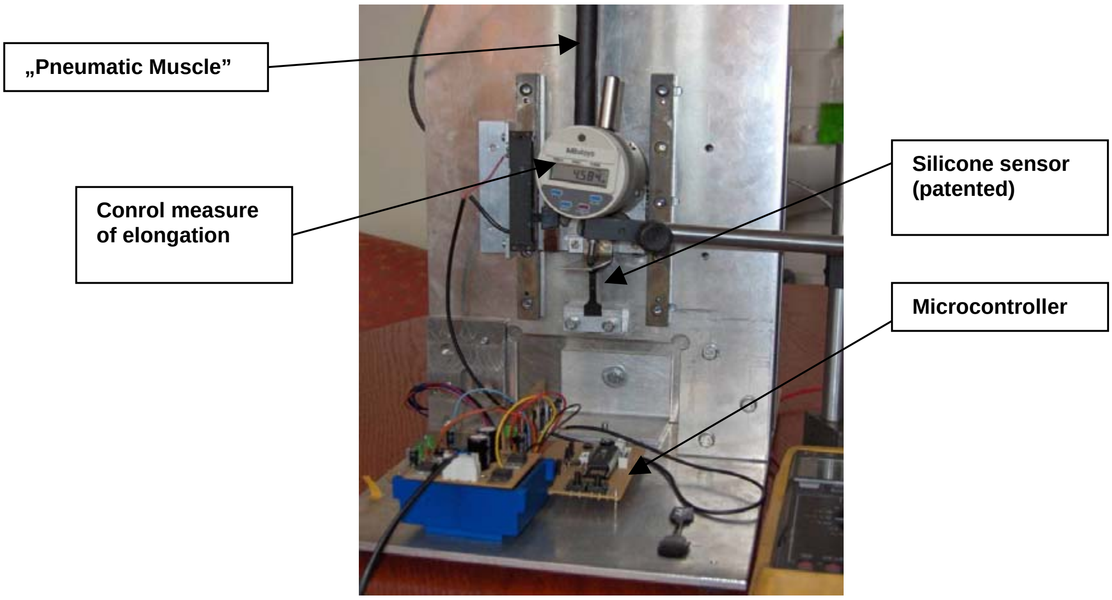


Fig. 14. Test equipment of the pneumatic control system with silicone rubber (patented) sensor

COMBINATION OF SILICON RUBBER BASED ACTUATOR AND SENSOR

The idea to couple the silicon rubber sensor with the special "Ferro-silicone" actuator developed by our research group was obvious for us since the sandwich construction has the same mechanical properties but with two different electric and magnetic behaviours. The sandwich construction is also patented in [7]**.** The combination of both materials allows the lay out of high elasticity constructions with control. The so called Ferro-silicone material is also a composite. The smart iron particles embedded in the silicone rubber structure allow the shape control of this high elasticity structure by electromagnetic field. About the realisation of a snail like locomotion system is reported in [9].

CONCLUSION

The silicon rubber is a relatively new material. We presented it for two new applications namely as sensor and as actuator in mechatronic systems. Since the exact material properties for the FEM simulations in the CAD process were not known a new material modelling method, the system synthesis was applied for the determination of the material models. This is a new method in the material science. We showed that pre-stressed conductive silicon rubber works like strain gauge for measuring of deformations in high elasticity constructions. The design of this type of constructions especially for the use in the field of controlled pneumatics has been presented. The combination of both structures as integrated sensor-actuator will induce new ideas in the industrial applications.

APPENDIX

This research work was supported by the Hungarian grants OTKA T 048386 and OTKA T 037526.

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