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# Non-monotonic sensor behavior of carbon particle-filled textile strain sensors


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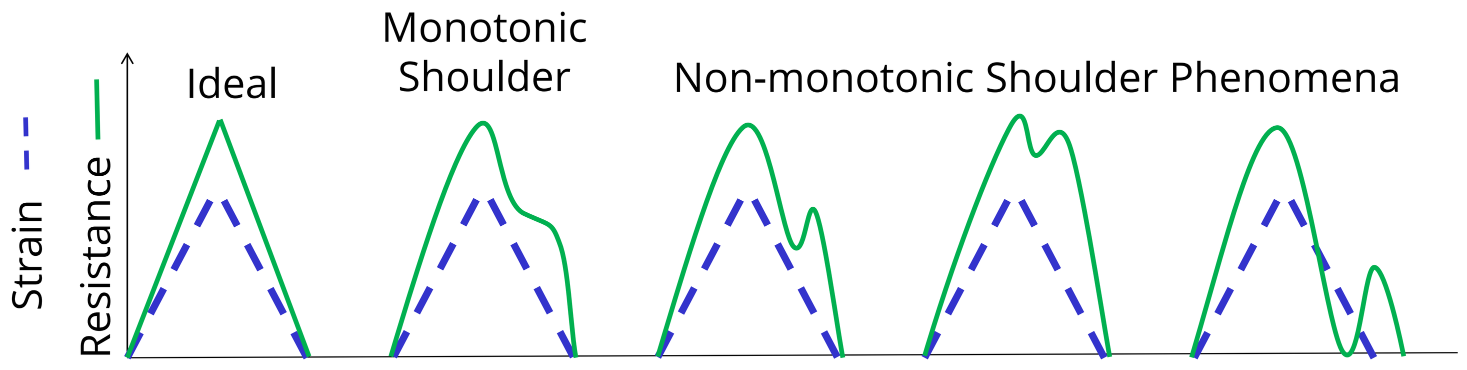
## Abstract

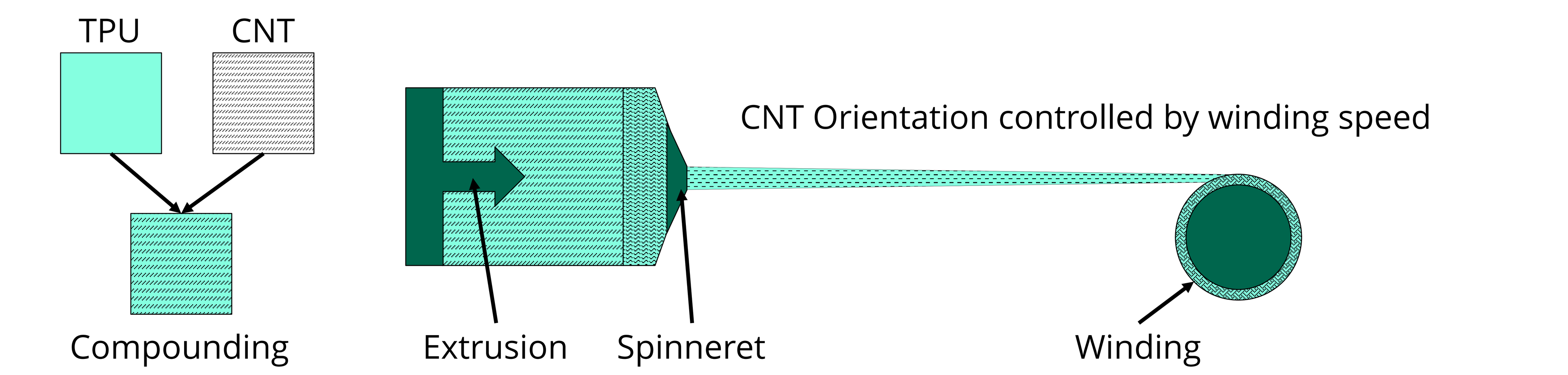
Carbon particle-filled elastomers are a widely researched option to be used as piezoresistive strain sensors for soft robotics or human motion monitoring. Therefore, various polymers can be com-pounded with carbon black, carbon nano tubes (CNT) or graphene. However, in many studies the electrical resistance's strain response of the carbon-particle filled elastomers is non-monotonic in dynamic evaluation scenarios. The non-monotonic material behavior is also called shoulder phenomenon or secondary peak. Until today, the underlying cause is not sufficiently well under-stood. In this study, several influencing test parameters on the shoulder phenomena are explored like strain level, strain rate and strain history. Moreover, material parameters like CNT content and anisotropy are varied in melt-spun CNT filled thermoplastic polyurethane filament yarns and their non-monotonic sensor response is evaluated. Additionally, a theoretical concept for the un-derlying mechanism and thereupon-based model is presented. An equivalent circuit model is used, which incorporates the visco-elastic properties and the characteristic of the percolation network formed by the conductive filler material. The simulation results are in good agreement when compared to the experimental results.


## 1. Non-monotonic resistance response



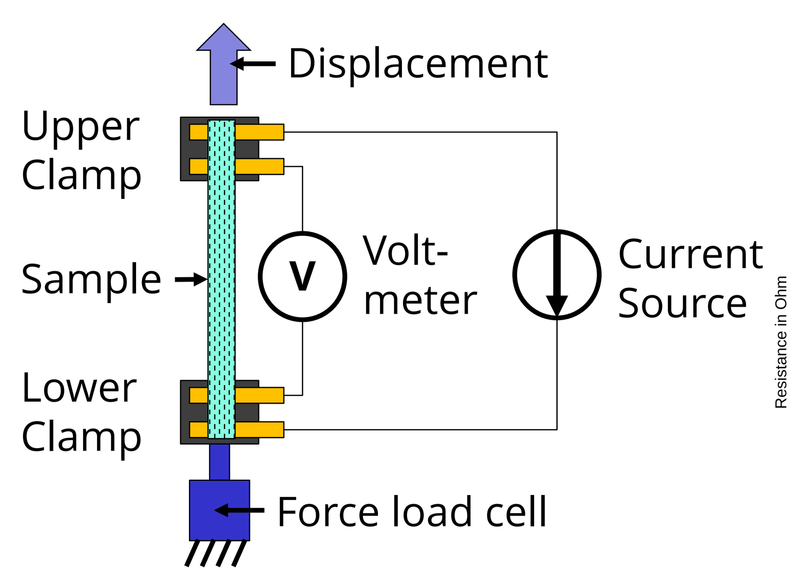

Apart from capacitive sensors, piezoresistive sensors based on the percolation network in carbon particle-filled elastomers are a frequently employed option. The working principle of these sensors is based on the high maximum stretchability of the elastomeric matrix material and the percolative network of the conductive fillers. Graphene, carbon nano tubes (CNT) and carbon black (CB) have been used as the conductive filler material in combination with a wide variation of matrix materials. Under dynamic loading conditions many of these carbon particle-filled elastomers show non-monotonic strain resistance behavior. The non-monotonic behavior is also called shoulder phenomenon or secondary peaks and occurs regardless of specific carbon particle type.

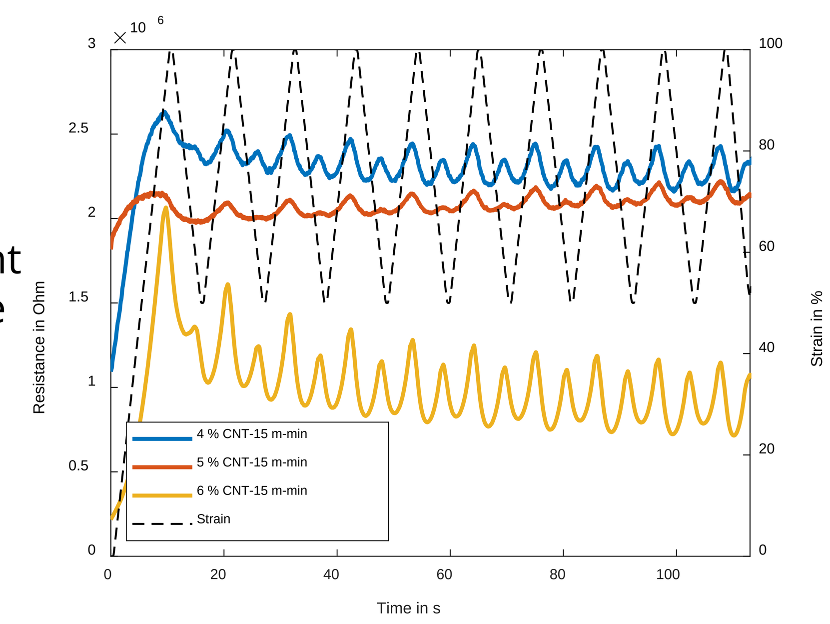
## 2. Melt spinning of highly stretchable CNT yarns




The electroconductive filament yarns were manufactured using a melt-spinning plant with thermoplastic polyurethane and CNTs. During the melt spinning process the CNT filler content was varied to influence the base conductivity of the resulting polymer. Filler contents <= 3 wt.% lead to enormous specific resistivities of > 2e5 Ohm*cm. Due to the significant disadvantages of such high resistivities for sensor applications, only filler contents of 4, 5 and 6 wt.% were evaluated.
The anisotropy was altered by changing the winding speed. A higher winding speed lead to a higher orientation of CNTs in fiber direction, which in turn effects the conductivity in longitudinal and transversal direction. The winding speed was varied from 10 to 15 and 17 m/min [1].

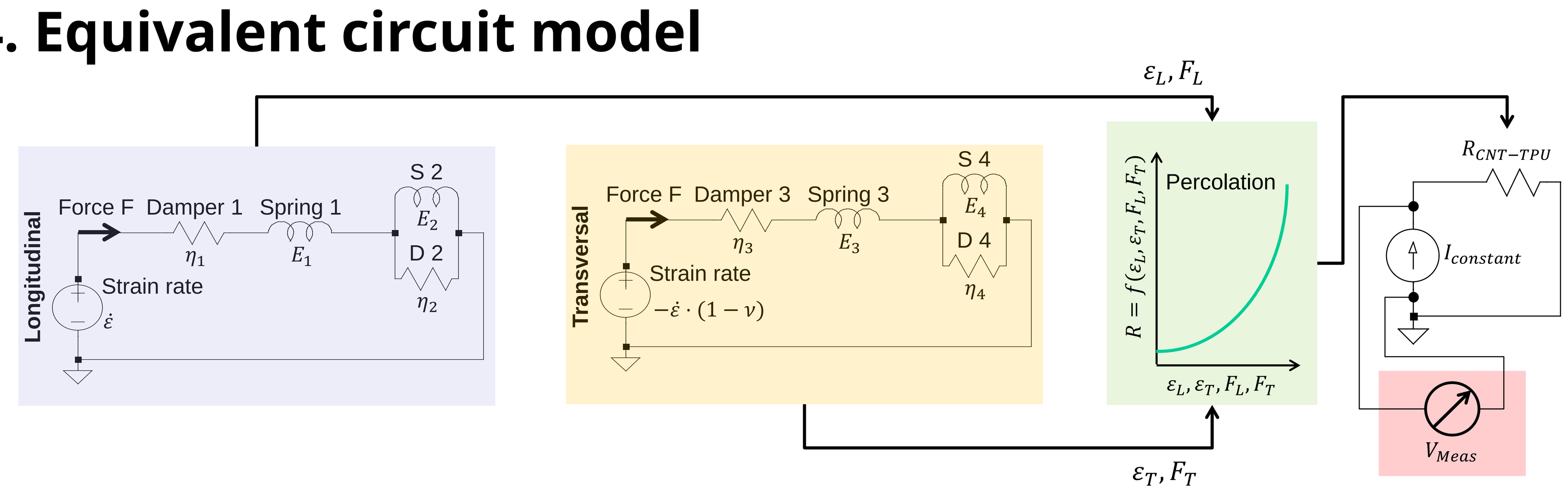
## 3. Electromechanical characterization




To evaluate the sensing behavior of the conductive yarns, cyclic tensile tests with accompanying resistance tracking were carried out. Because a part of the strain during the first cycle is not recoverable, the yarns were strained to 100 % and then cycled be-tween 50 and 100 % strain. This eliminates the occurrence of negative forces and bent yarns, when retracting to 0 %. For each parameter combination at least 9 samples were tested or 10 loading cycles each. Afterwards the resistance and force data were averaged.

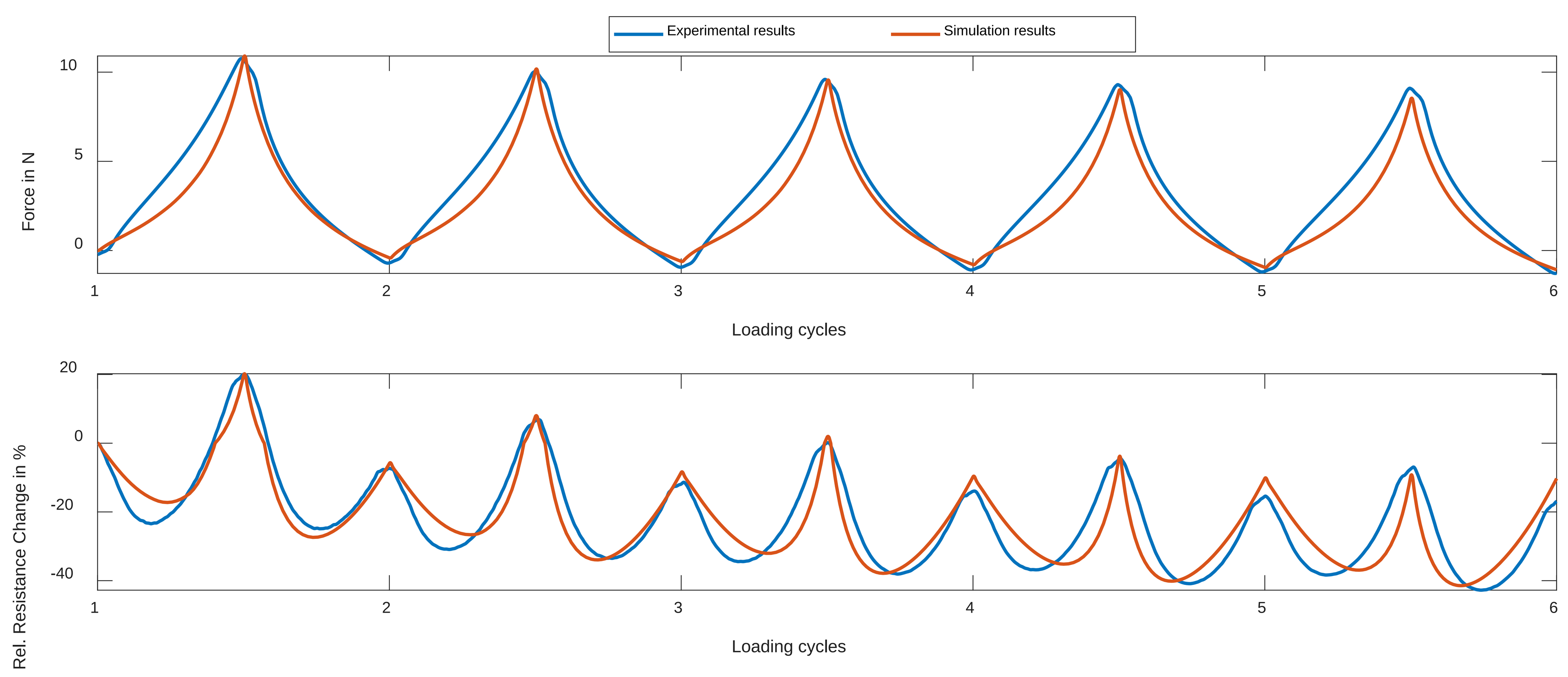
## 4. Equivalent circuit model




The equivalent circuit model represents the visco-elastic nature of the polymer by a Burger's model. One for the response in longitudinal direction, and one in transversal direction. The strain and stress response are then forwarded to a percolation model, which emulates the relation as an exponential function. From there the resistance of the sample is calculated [2].
In order to evaluate the characteristics of the conductive yarns, the model's parameters were fit to the experimental results. This fitting procedure was divided into three steps. First, the tensile testing scenario was emulated by a cyclic, stepping voltage source. Second, the parameters of the Burger's model representing the longitudinal mechanical domain were fitted to match the measured force curve. Last, the remaining parameters were varied to minimize the difference between simulated and experimental resistance.

## 5. Results

The force and resistance response to the cyclic strain loading is shown for CNT yarns with a constant winding speed of 15 m/min but different filler contents. With rising filler content, the elastic modulus increased as expected. The base resistance of the 5 wt.% CNT samples was higher than that of the 4 wt.% ones. However, as to be expected, after the first loading cycle the resistivity for the material with lower CNT content rose significantly. Thus, the conductivity in-creased with a higher CNT content. Additionally, the same set-up was used to evaluate yarns with a CNT filler content of 6 wt.% with varying winding speeds. At an increasing winding speed the amount of CNT oriented in fiber direction, the maximum force, the modulus and the base resistance increase. At the same time the diameter of the fiber decreases. If the smaller cross-section of the yarn is taken into account, the Young's modulus increases.
Lastly, the simulation results of the equivalent circuit model are shown on the right. The theoretical results are in good agreement with the experimental results both for the longitudinal force as well as the relative change in resistance.





## Acknowledgements

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## References


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