Mechanical Fatigue and Load-Induced Aging of Loudspeaker Suspension

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Questions addressed in the paper

- Why is the suspension the weakest loudspeaker part ?
- How to measure the long-term stability of soft parts ?
- How to consider the influence of the mechanical load on the aging ?
- How to separate the early break-in process from fatigue ?
- How to predict the final loss of stiffness ?
- How to design and select good suspension parts ?

Road Map

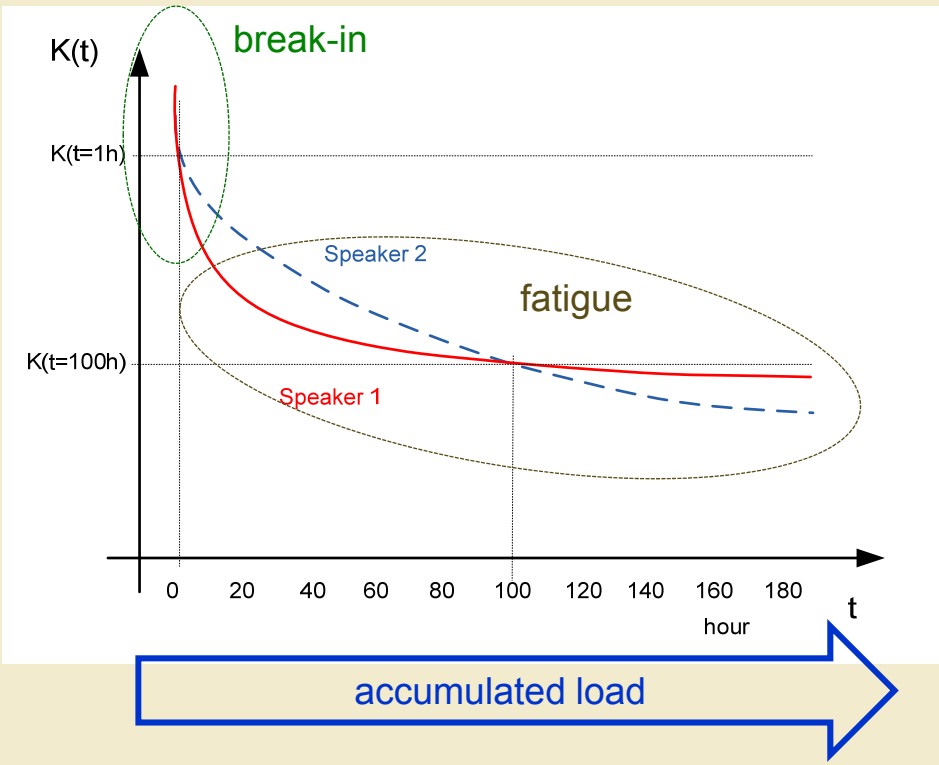
- Introduction (problem, history)
- Modeling of load-induced aging
- Measurement techniques
- Practical application (diagnostics)
- Conclusion

Variation of Suspension Stiffness K(t) versus Measurement Time t

Performing a power test with pink noise of constant amplitude

Stiffness ratio after 1 h and 100 h power testing

$$R_{100\text{h}} = \frac{K(t = 100\text{h})}{K(t = 1\text{h})}$$



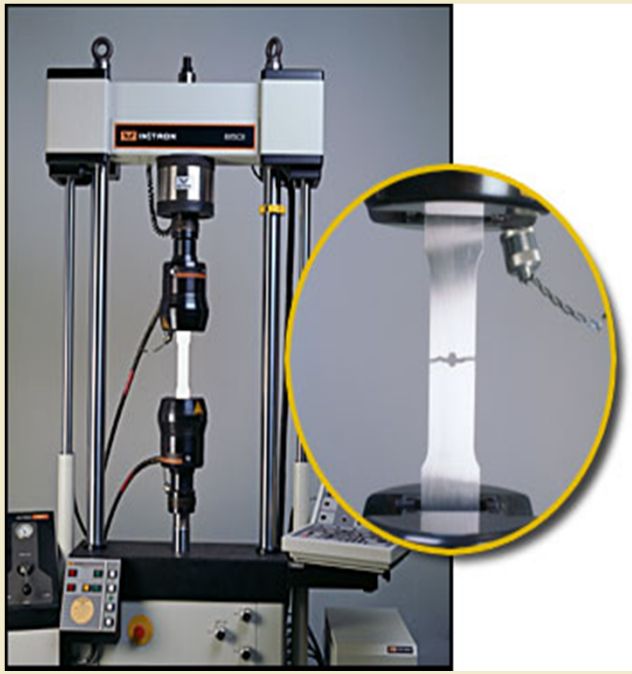
Disadvantages of :

- measurement results depends on the properties of the stimulus
- assumes constant excitation during power test
- can not be transferred to other stimuli
- neglects the slope of the stiffness variation

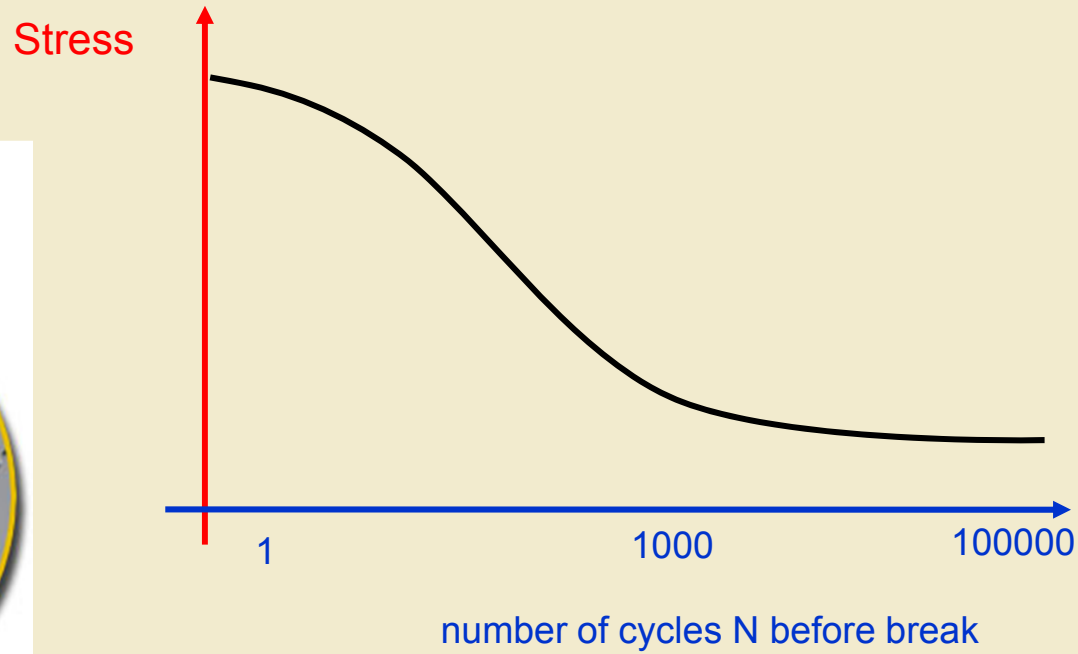
Idea:
Replacing time t by a quantity describing the dosage of the mechanical load

Conventional Measurement of Fatigue

S-N Curves (Wöhler) show the sinusoidal stress S and number of cycles N causing a failure



Courtesy by Coldwork.com



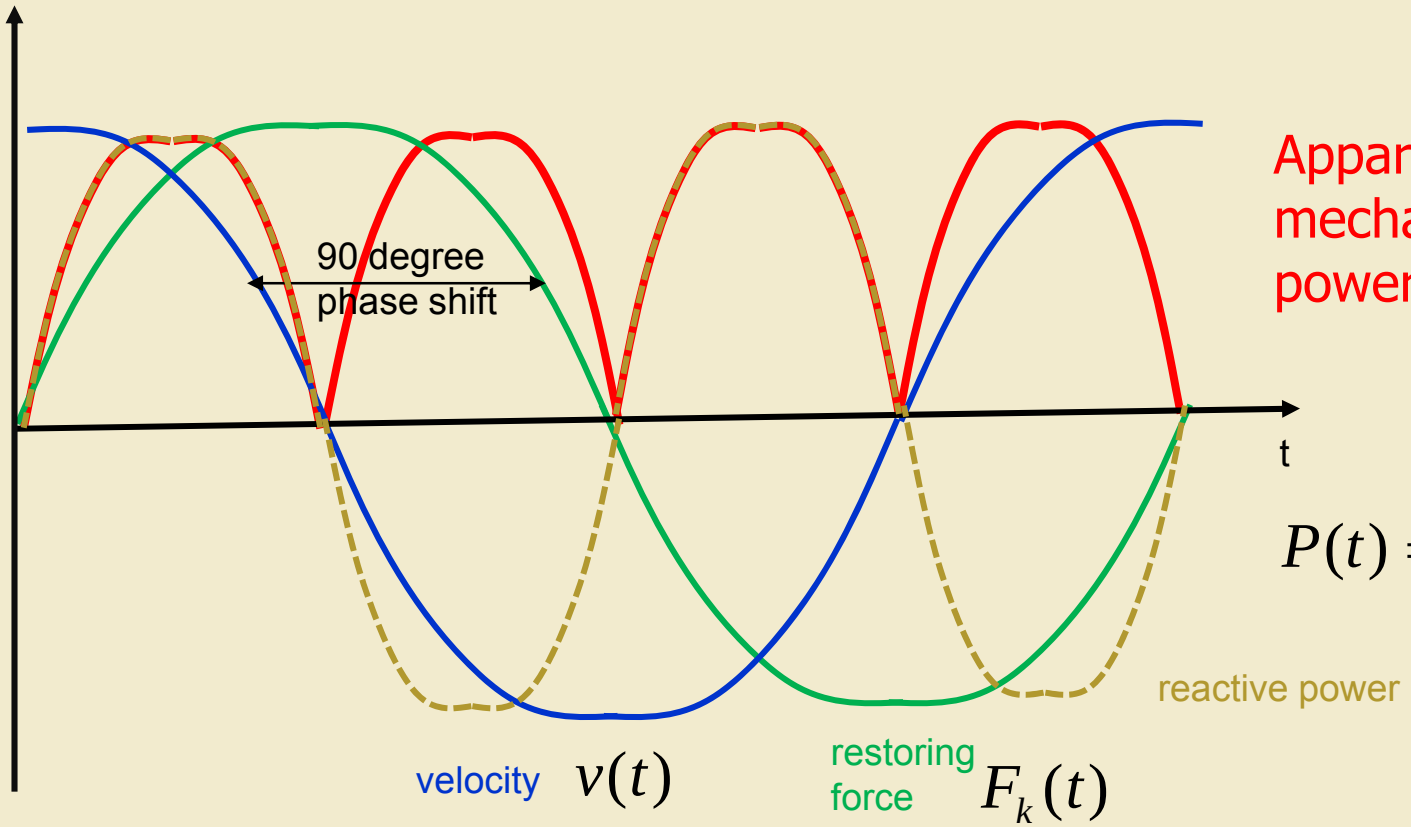
→ cannot be directly applied to loudspeaker suspensions because we are interested in the stiffness variation before a fatal break occurs

Loudspeaker Suspension

The load-induced variation of the stiffness depends on

- the potential energy temporarily stored in the suspension considering the nonlinear force-deflection characteristic,
- energy dissipated into heat by losses in the material,
- frequency (cycles) of an alternating stimulus,
- accumulated power transferred to the suspension part during life time of the suspension,
- other unknown factors …

How to define the Mechanical Load ?



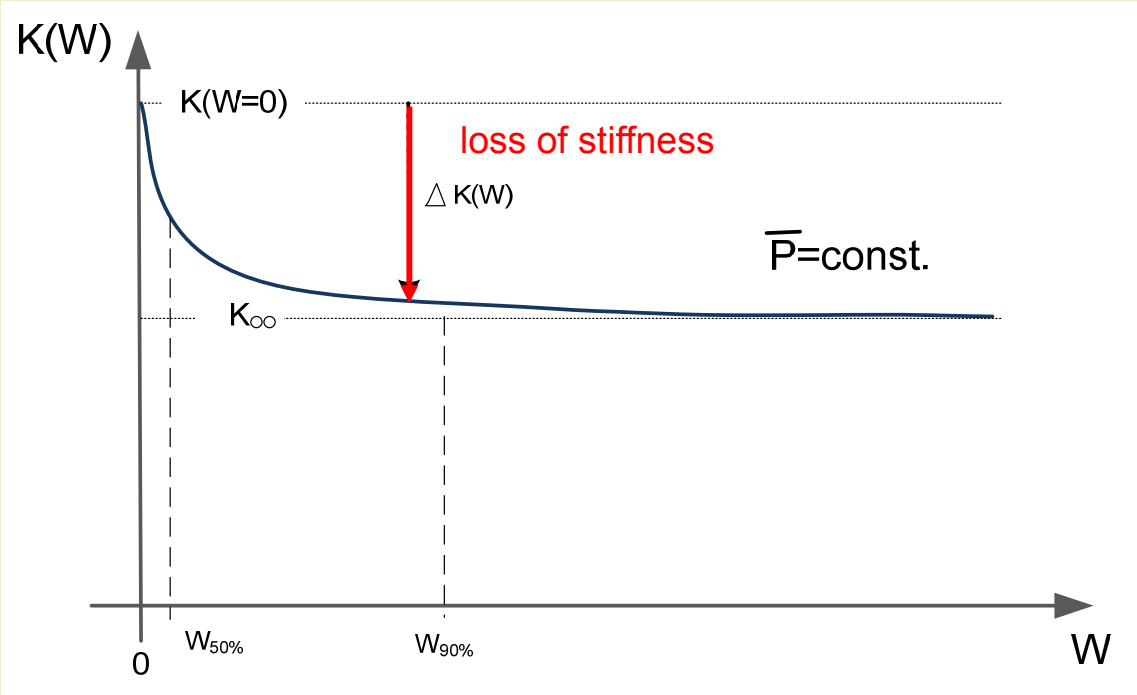
Apparent mechanical power

$$P(t) = \left| F_{\mathrm{k}}(t) v(t) \right|$$

Apparent mechanical work performed on the suspension over life time

$$W(t_{\mathrm{m}}) = \int_0^{t_{\mathrm{m}}} P(t)dt = \overline{P} t_{\mathrm{m}}.$$

Constant Load Model



Measurement Condition:

same stimulus of constant amplitude during the power test

Stiffness of loudspeaker suspension versus accumulated work W

$$\hat{K}(W) = K(W=0) - \Delta K(W)$$

$$\Delta K(W) = \sum_{i=1}^{N} C_i \left(1 - e^{-W/w_i}\right)$$

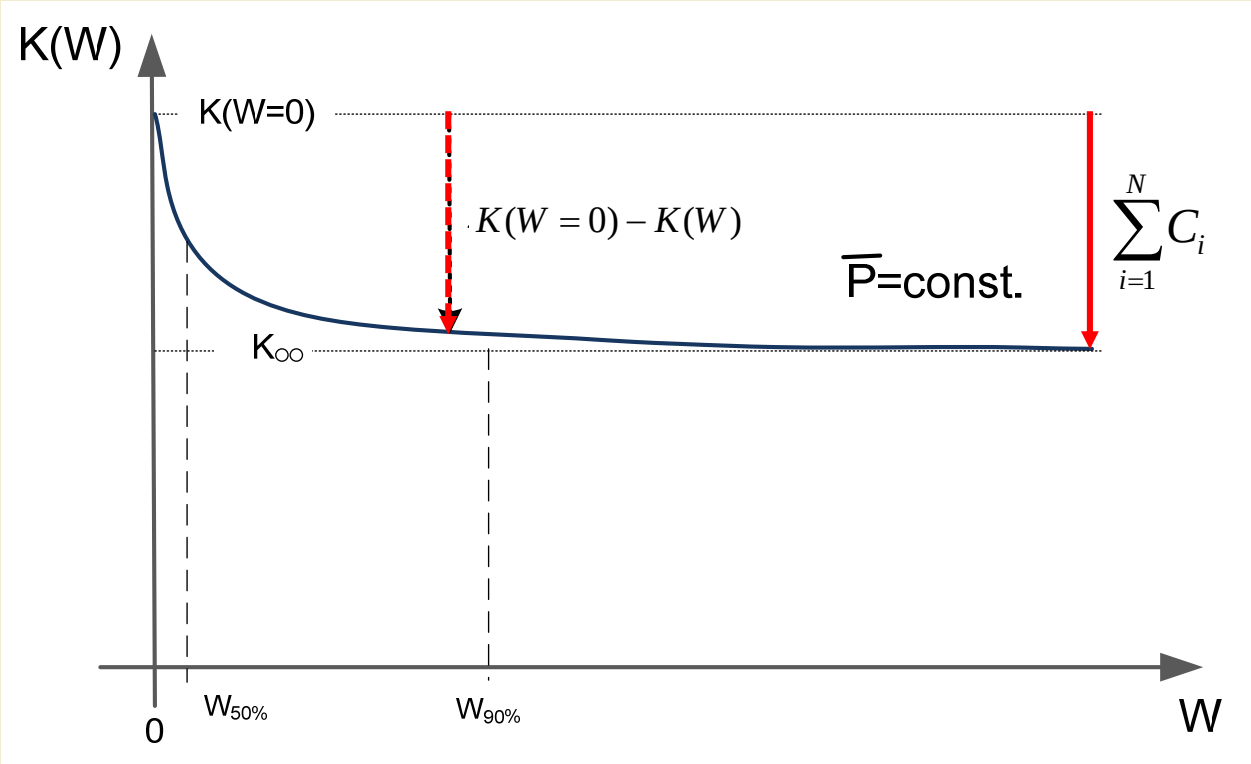
N=2 sufficient for most cases

1st Characteristic: Relative Aging Ratio

Definition:

$$a(W) = \frac{K(W=0) - K(W)}{\sum_{i=1}^{N} C_i} 100\ \%$$

- describes the progress of the ageing process in percent
- approaches 100 % for infinite work



$$a(W_{50\%}) = 50\% \qquad a(W_{90\%}) = 90\%$$

Derived Characteristics:

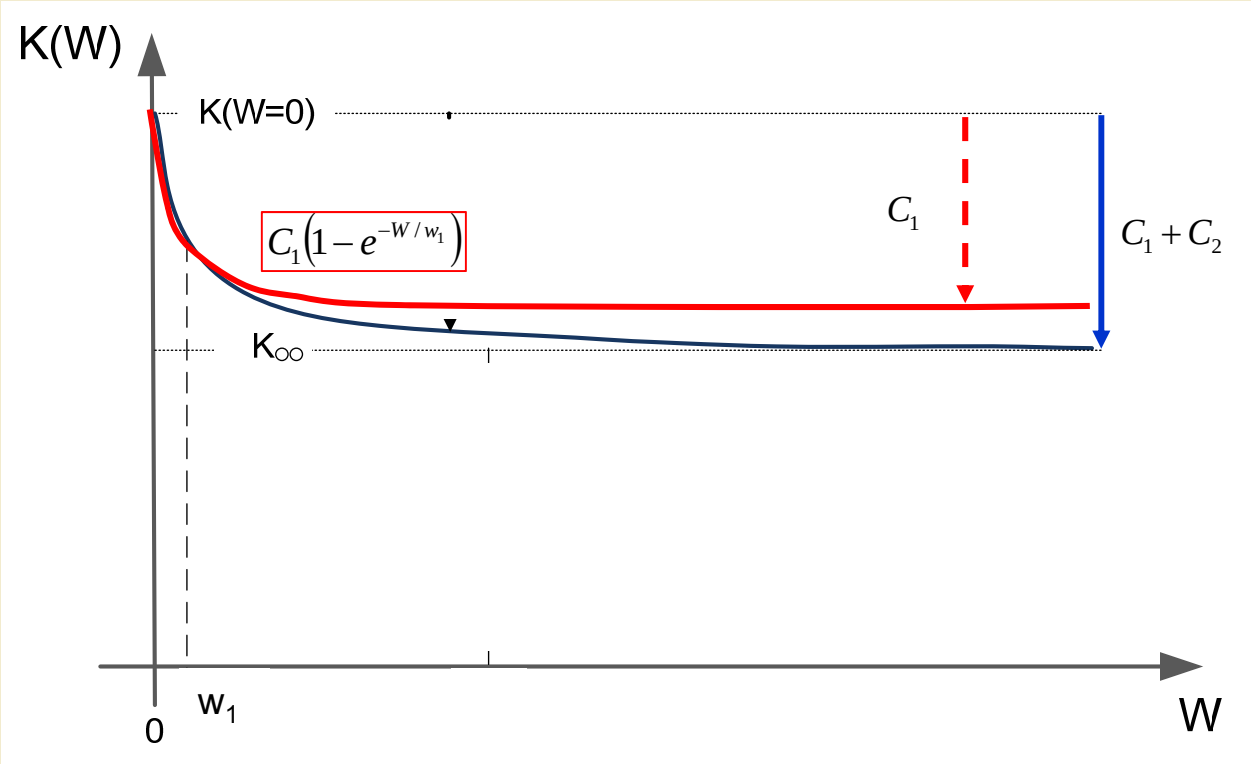
final value of stiffness

$$\hat{K}(W \to \infty) = \hat{K}_{\infty} = K(0) - \sum_{i=1}^{N} C_i .$$

Total loss of stiffness during life time

$$V_a = \frac{\sum_{i=1}^{N} C_i}{K(W=0)} 100\%$$

2nd Characteristic: Break-in Ratio



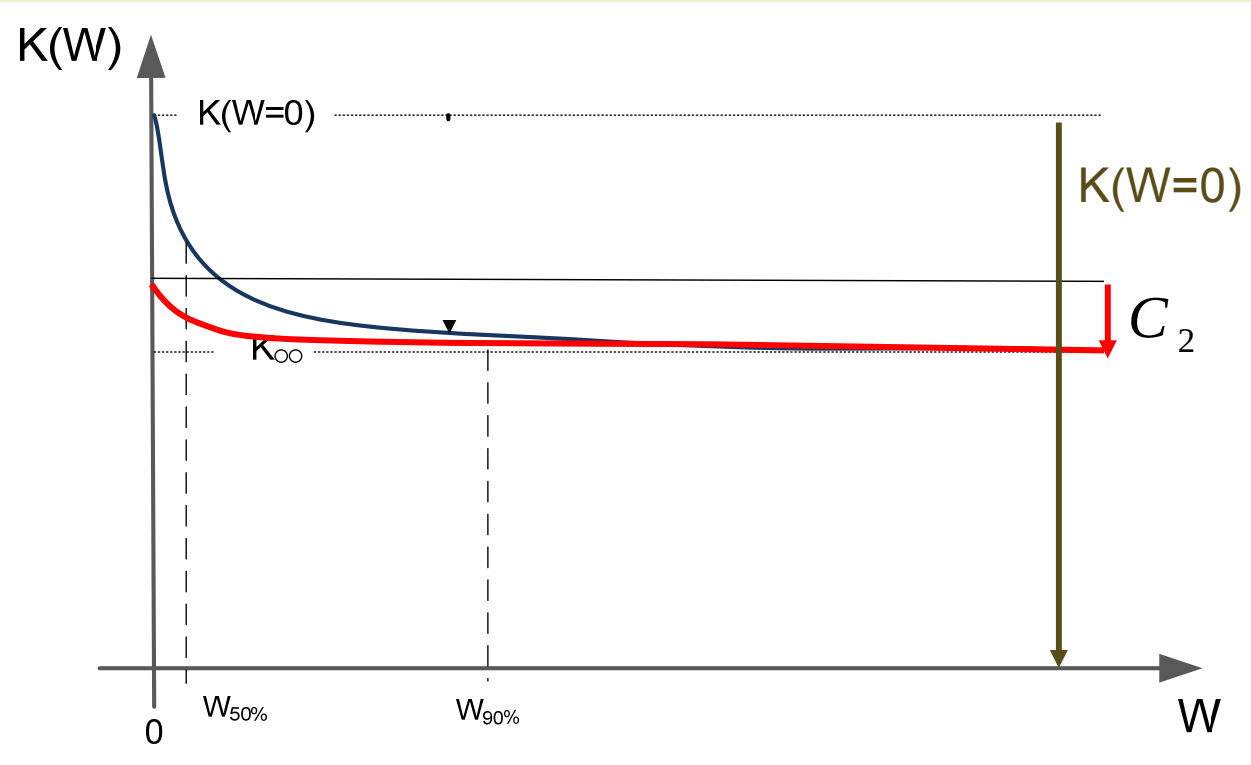
Definition:

$$R_b = \frac{C_1}{C_1 + C_2} 100\% \quad \Big| N = 2$$

The simple model for *N*=2 is a good approximation of most suspension parts and separates the break-in effect generating the steep decay at the beginning of the aging process from the fatigue causing a much slower decay at large values of accumulated work *W*.

w_1 describes the amount of work required to complete 63% of the break-in phase.

3rd Characteristic: Total Fatigue Loss



Definition:

$$V_f = \frac{C_2}{K(W=0)} 100\% \quad \Big| N = 2 \quad .$$

describes the percentage of stiffness loss due to fatigue

If the break-in effect is dominant ($R_b \approx 100\ \%$) and fatigue negligible ($V_f \approx 0$) then we find the relationship $W_{90\%} \approx 3W_{50\%}$.

Important Quality Criteria

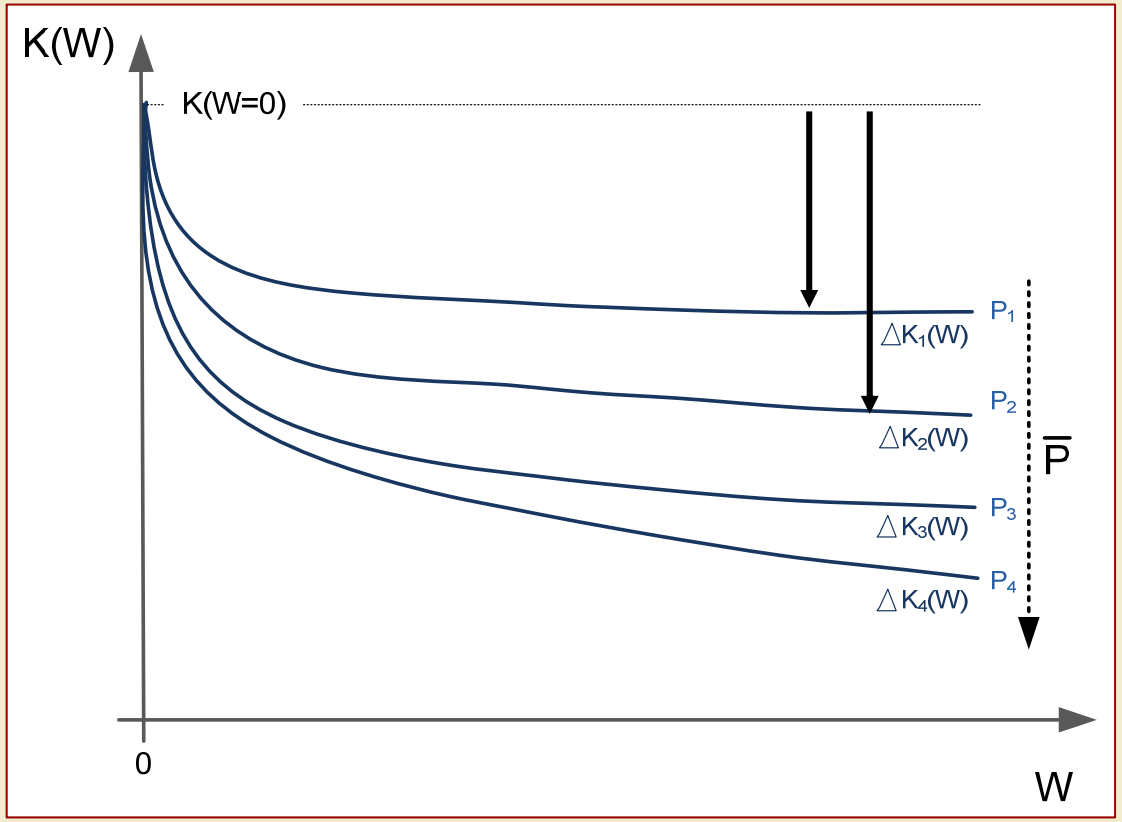
for assessment the stability of suspension parts

Criteria	Optimal value	Priority
Minimal fatigue	$V_f = 0\%$	1
Dominant break-in	$R_b = 100\ \%$ $W_{90\%} \approx 3W_{50\%}$	2
Slow fatigue process	$w_2 > W_a$	3
Total aging ratio	$V_a = 0\ \%$ at the moment not realistic !	4
Fast break-in process	$w_1 << W_a$	5

Nominal value for designing transducers: $K_{nom} = K(W = 0) - C_1 \quad \big| N = 2$

Influence of the Power Level P

on Load-Induced Aging of the Suspension



Measurement Methodology:

1. Selecting units of the same type with similar properties
2. Applying a constant but different mechanical power P_j to each unit and measuring the variation of $K(W_j)$
3. Fitting the constant load model to the $K(W_j)$ characteristic of each unit

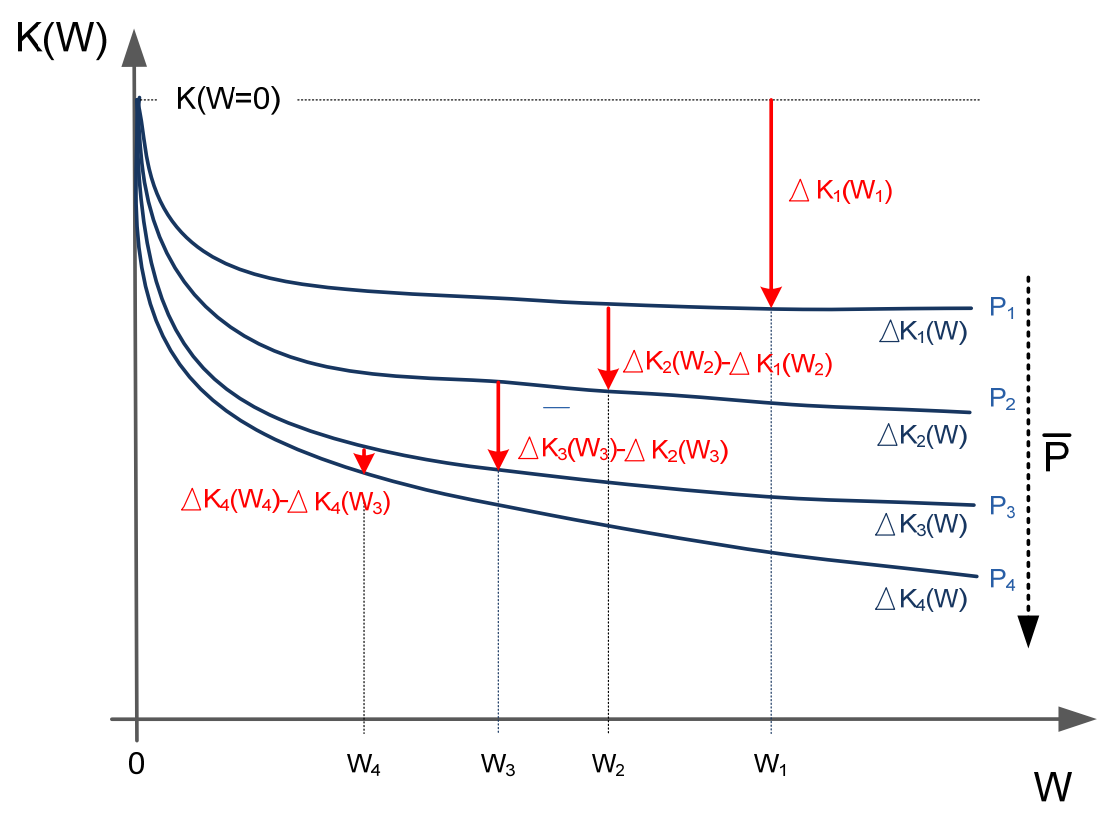
$$\Delta K_j(W_j|P_j) = \sum_{i=1}^{N} C_{j,i}\left(1 - e^{-W_k / w_{k,i}}\right) \quad \Bigg| \begin{array}{l} \overline{P} = P_j = const \\ j = 1,\ldots,J \end{array}$$

A set of ageing functions $K(W_j)$ measured at constant mechanical power P_j

Varying Load Model

Objectives:

- To consider the dependency on instantaneous power level
- To predict the stiffness variation for any stimuli



$$\hat{K}(W) = K(W=0) - \sum_{j=2}^{J}\left(\Delta K_j(W_j) - \Delta K_{j-1}(W_j)\right) - \Delta K_1(W_1)$$

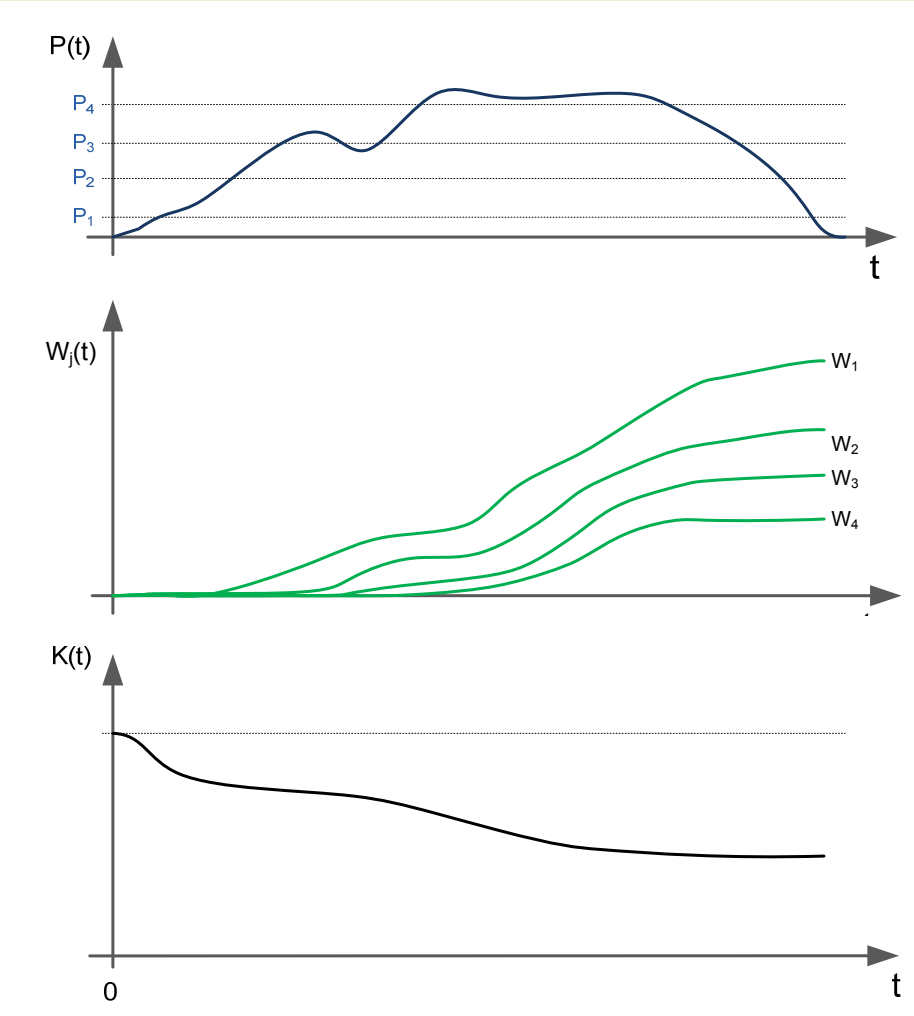
using multiple states W_j accumulating the power $P(t)$ above the power value P_j using the window function $g_j(t)$

$$W_j(t_0) = \int_0^{t_0} g_j(t)P(t)dt \qquad j = 1,\ldots,J$$

$$g_j(t) = \begin{cases} 1 & \text{if} \quad P \geq P_j \\ 0 & \text{otherwise} \end{cases} \qquad j = 1,\ldots,J$$

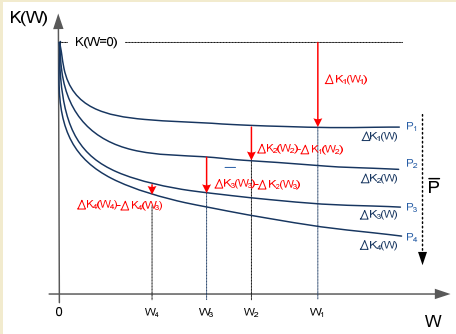
Calculation of Stiffness K(t)

for an Arbitrary Power Profile P(t)



dividing in power levels

Measurement Results



accumulation in the work variables

$$W_j(t_0) = \int_0^{t_0} g_j(t) P(t) dt \qquad j = 1,\ldots,J$$

$$g_j(t) = \begin{cases} 1 & \text{if} \quad P \geq P_j \\ 0 & \text{otherwise} \end{cases} \qquad j = 1,\ldots,J$$

$$\hat{K}(W) = K(W=0) - \sum_{j=2}^{J} \left(\Delta K_j(W_j) - \Delta K_{j-1}(W_j) \right) - \Delta K_1(W_1)$$

Measurement Technology

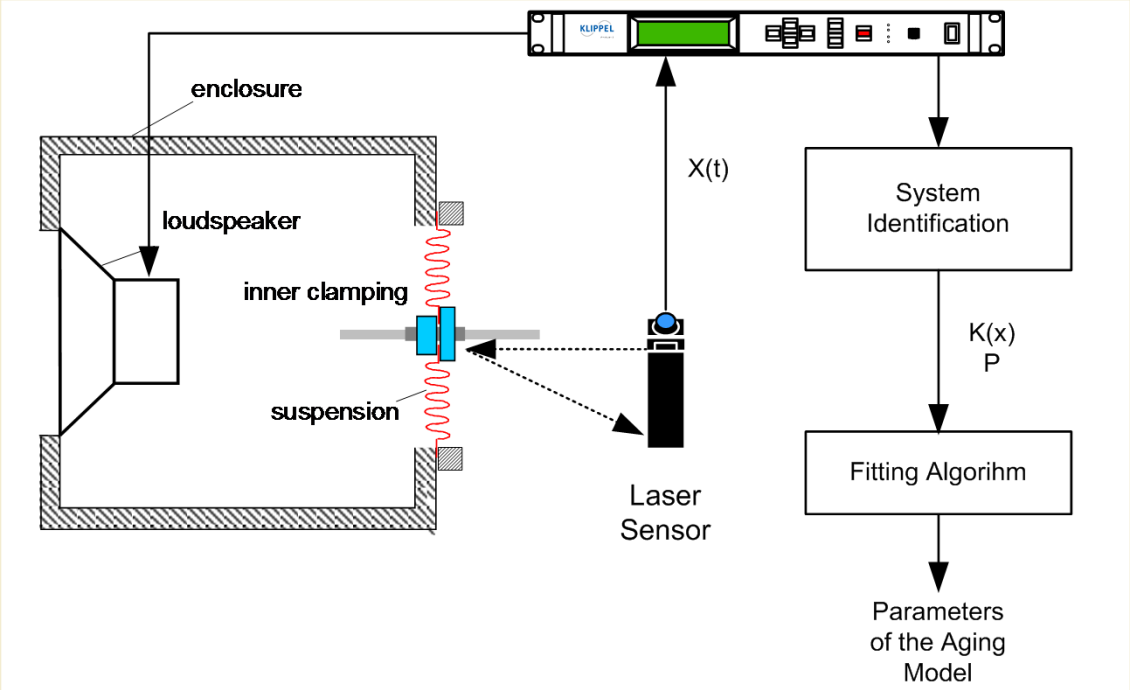
Part 1: Suspension Parts

apparent mechanical power

$$P(t) = \left| K(x)x(t)\frac{dx(t)}{dt} \right|$$

displacement sensor

nonlinear system identification

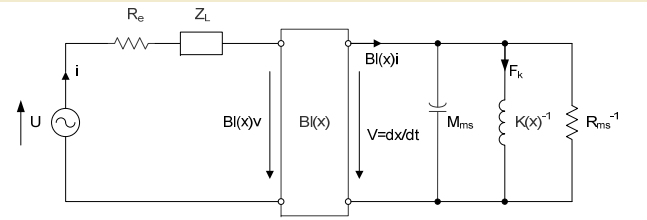


Measurement of spiders, surrounds and passive radiators using a laser sensor and system identification

Measurement Technology

Part 2: Electro-dynamical Transducer

Electro-mechanical equivalent circuit of the loudspeaker system

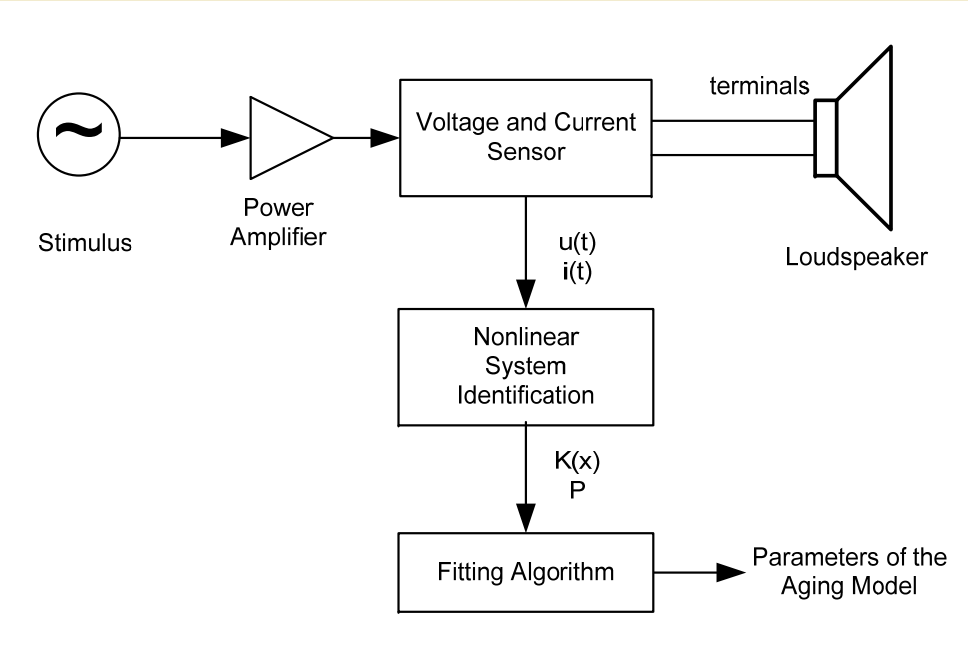


apparent mechanical power

$$P(t) = \left|F_k(x)v(t)\right| = \left|K(x)x(t)v(t)\right|$$

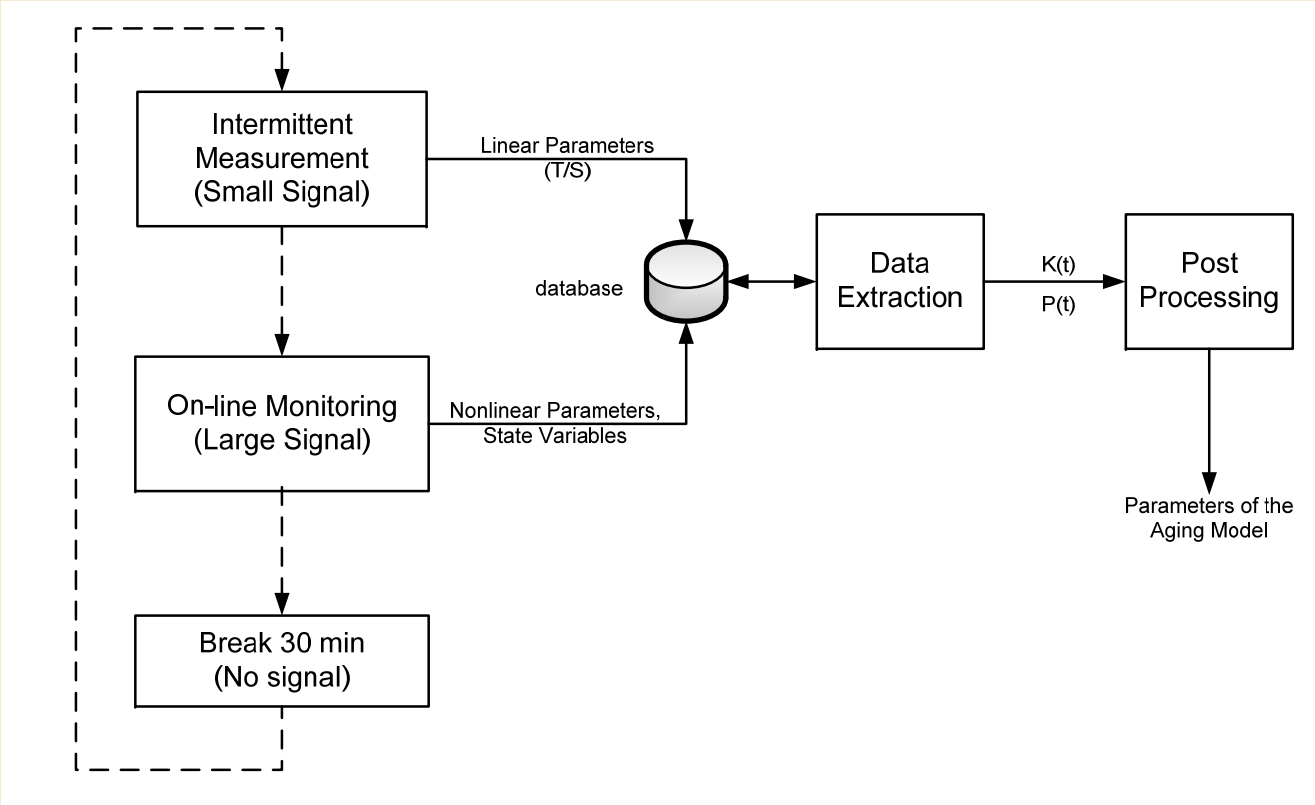
$$= \left|\frac{K(x)}{Bl(x)}x(t)Bl(x)v(t)\right|$$

$$= \left|i_k(t)u_{emf}(t)\right|$$



System identification based on voltage and current signals measured at the loudspeaker terminals

Long-Term Monitoring
of Loudspeaker Suspension



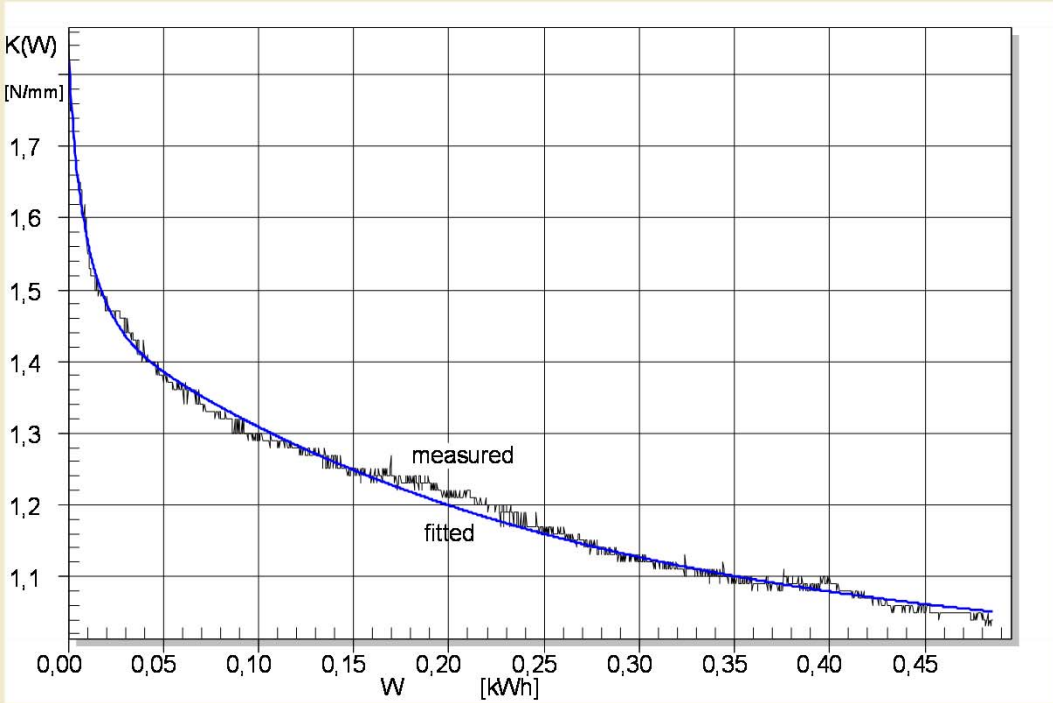
model fitting

$$C = \sum_{m=1}^{M} \left(K(W(t_m)) - \hat{K}(W(t_m)) \right)^2 \rightarrow \quad \min.$$

Long-term monitoring by looping a sequence of measurements and post-processing of the collected data.

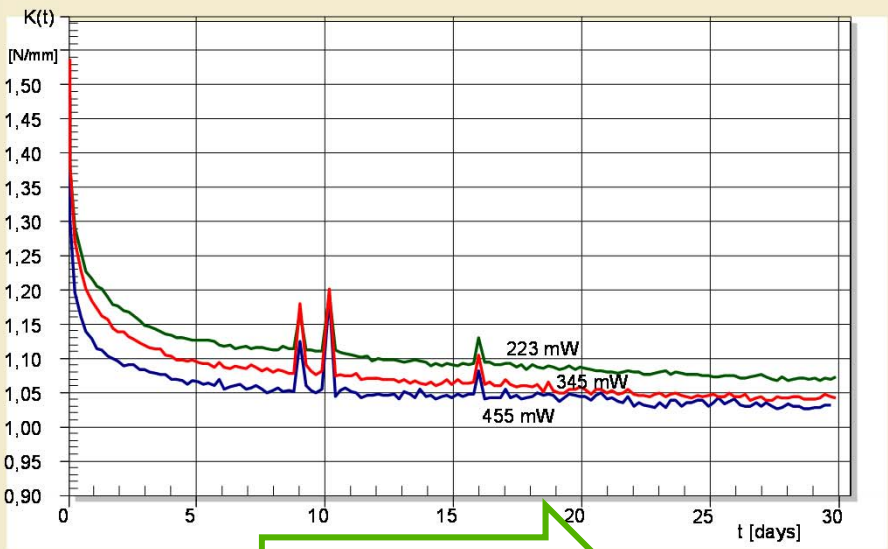
Example: Poor Spider

Suffering from Long-Term Fatigue

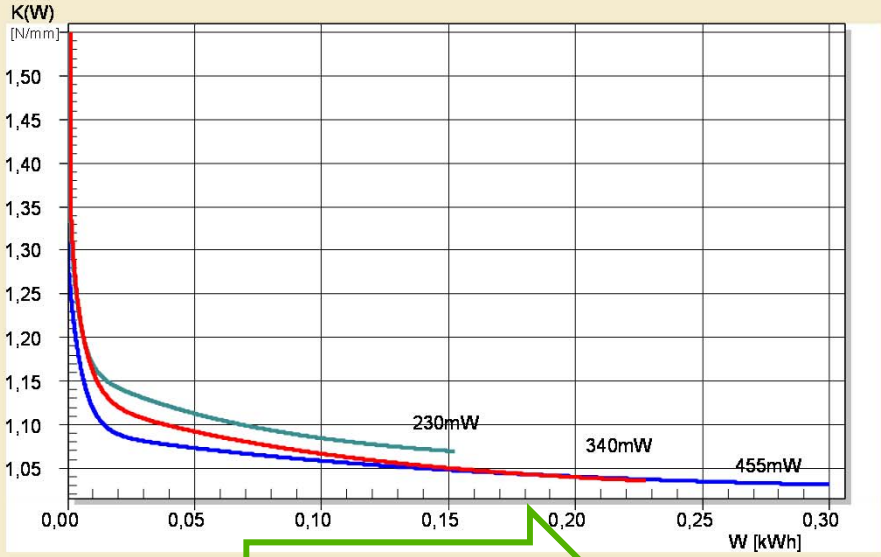


- $V_a \approx 50\%$ → half of the initial stiffness will disappear during the life-cycle of the suspension part.
- $R_b \approx 50\ \%$ → only half of the changes occur during the relative short break-in process requiring only $w_1 = 0.02$ kWh.
- $V_f \approx 22\ \%$ → high fatigue ratio causes a permanent but slow decay of the stiffness
- $W_{90\%} = 0.42$ kWh $\approx 11 W_{50\%}$ → high value of the accumulated work is required to approach
- 90 percent of the final value $K_\infty = 0.9$ N/mm (predicted)

Example: Loudspeaker A



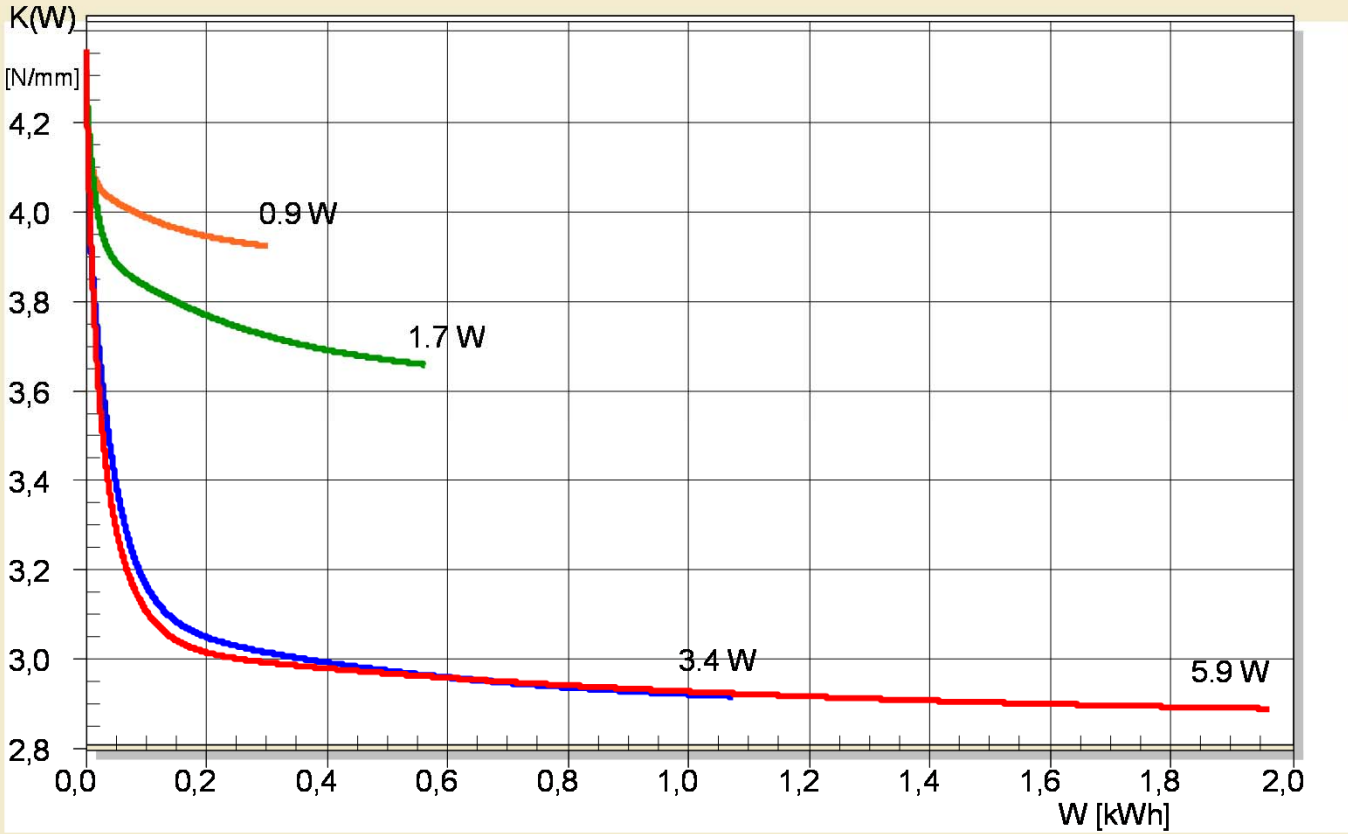
Time



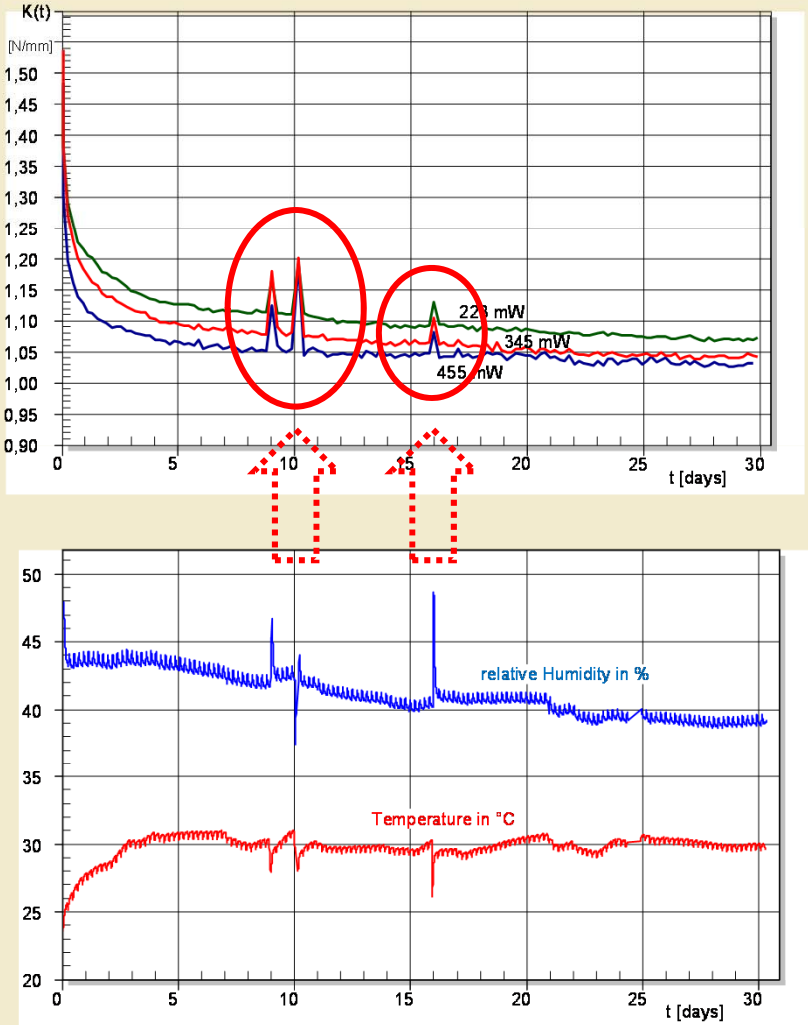
Work

- $V_a \approx 30$ % → small aging ratio
- $R_b \approx 85$ % → most of the variations occur during the dominant break-in process
- $W_{90\%} \approx 0.1$ kWh → small amount of work is required to approach 90 % of the final stiffness value.
- Levels are very similar → low dependency on power level

Example: Loudspeaker B



Influence of Ambient Condition



- Ambient temperature and humidity have a strong influence on the stiffness K of the suspension
- The ambient condition should be constant during the aging test
- Fitting algorithm provided with sufficient data collected at high sampling rate can compensate for short variation

Conclusions

Load-induced aging of the suspension material

- can be described by a dosage model using mechanical apparent work W as state variable
- few aging parameters can be identified from stiffness K(t) and apparent power P(t) recorded in long-term tests
- The stiffness variation K(t) versus time can be predicted for any stimulus using the power profile P(t)
- the model has been verified on a variety of suspension parts and assembled transducers
- The model predicts the final stiffness K_∞ and the intensity and dynamics of the aging process
- Short break-in effect can be easily separated from the long-term fatigue effect
- The stiffness K_{nom} found after break-in is a useful nominal characteristic of the suspension part
- A low fatigue loss of stiffness expressed by V_f reveals the long-term stability of the suspension