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

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

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.

→ 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

\[ P(t) = |F_k(t)v(t)| \]

90 degree phase shift

Apparent mechanical work performed on the suspension over life time

\[ W(t_m) = \int_0^{t_m} P(t) dt = \bar{P} t_m. \]
**Constant Load Model**

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

**Measurement Condition:**
same stimulus of constant amplitude during the power test
1st Characteristic: Relative Aging Ratio

Definition:

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

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

\[ K(W) \]

\[ K(W=0) \]

\[ K_\infty \]

\[ W_{50\%} \]

\[ W_{50\%} \]

\[ K(W = 0) - K(W) \]

\[ \sum_{i=1}^{N} C_i \]

Derived Characteristics:

- final value of stiffness
  \[ \hat{K}(W \to \infty) = \hat{K}_a = K(0) - \sum_{i=1}^{N} C_i. \]

- Total loss of stiffness during life time
  \[ V_a = \frac{\sum_{i=1}^{N} C_i}{K(W = 0)} \times 100\% \]

\[ a(W_{50\%}) = 50\% \]

\[ a(W_{90\%}) = 90\% \]

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2nd Characteristic: Break-in Ratio

Definition:

\[ R_b = \frac{C_1}{C_1 + C_2} \times 100\% \quad |N = 2 \]

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.

\( \frac{C_1(1 - e^{-W/w_1})}{C_1 + C_2} \)
3rd Characteristic: Total Fatigue Loss

Definition:

\[ V_f = \frac{C_2}{K(W=0)} \times 100\% \quad |N = 2 \]

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

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Optimal value</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal fatigue</td>
<td>( V_f = 0% )</td>
<td>1</td>
</tr>
<tr>
<td>Dominant break-in</td>
<td>( R_b = 100% ) ( W_{90%} \approx 3W_{50%} )</td>
<td>2</td>
</tr>
<tr>
<td>Slow fatigue process</td>
<td>( w_2 &gt; W_a )</td>
<td>3</td>
</tr>
<tr>
<td>Total aging ratio</td>
<td>( V_a = 0% )</td>
<td>4</td>
</tr>
<tr>
<td>Fast break-in process</td>
<td>( w_1 &lt;&lt; W_a )</td>
<td>5</td>
</tr>
</tbody>
</table>

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

\[ \Delta K_j(W) | P_j = \sum_{i=1}^{N} C_{ij} \left(1 - e^{-W_j/W_{ij}}\right) \quad \bar{P} = P_j = \text{const} \quad j = 1, ..., J \]

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

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

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

\[
W_j(t_0) = \int_{0}^{t_0} g_j(t)P(t)dt \quad j = 1, \ldots, J
\]

\[
g_j(t) = \begin{cases} 
1 & \text{if } P \geq P_j \\
0 & \text{otherwise}
\end{cases} \quad j = 1, \ldots, J
\]
Calculation of Stiffness $K(t)$ for an Arbitrary Power Profile $P(t)$

\[
W_j(t_0) = \int_0^{t_0} g_j(t)P(t)\,dt \quad j = 1, \ldots, J
\]

\[
g_j(t) = \begin{cases} 
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\dot{K}(W) = K(W = 0) - \sum_{j=2}^J \left( \Delta K_j(W_j) - \Delta K_{j-1}(W_j) \right) - \Delta K_1(W_1)
\]
Measurement Technology
Part 1: Suspension Parts

apparent mechanical power

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

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

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Measurement Technology
Part 2: Electro-dynamical Transducer

Electro-mechanical equivalent circuit of the loudspeaker system

apparent mechanical power

\[ P(t) = |F_k(x)v(t)| = |K(x)x(t)v(t)| \]

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

\[ = |i_k(t)u_{emf}(t)| \]
Long-term monitoring by looping a sequence of measurements and post-processing of the collected data.
Example: Poor Spider
Suffering from Long-Term Fatigue

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

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

![Graph showing the relationship between power (W) and force (K(W)) for Loudspeaker B with power levels of 0.9 W, 1.7 W, 3.4 W, and 5.9 W at different force levels.](image)
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 $K_\infty$ 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 $K_{\text{nom}}$ 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