Mechanical Fatigue and Load-Induced Aging of Loudspeaker Suspension

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Abstract

The mechanical suspension becomes more and more compliant over time changing the loudspeaker properties (e.g. resonance frequency) significantly. This aging process is reproducible and the decay of the stiffness can be modeled by accumulating the apparent power supplied to the suspension part and using an exponential relationship. The free parameters of this model are estimated from empirical data provided by on-line monitoring or intermittent measurements during regular power tests or other kinds of long-term testing. The identified model can be used to predict the load-induced aging for music or test signals having arbitrary spectral properties. New characteristics are being introduced which simplify the quality assessment of suspension parts and separate mechanical fatigue from the initial break-in effect. Practical experiments are performed to verify the model and to demonstrate the diagnostic value for selecting optimal suspension parts providing sufficient long-term stability.

1. INTRODUCTION

Spiders, surrounds and other soft parts used as a mechanical suspension in electro-acoustical transducers vary significantly over time. Variation of the stiffness $K(x=0)$ at the rest position affects the fundamental resonance frequency and the alignment of the drive unit in a vented enclosure. A loss of stiffness increases the peak displacement which may result in hard limiting of the voice coil former at the back plate or coil rubbing at the pole tips. In combination with a nonlinear force factor characteristic $Bl(x)$ a softer suspension may also cause a motor instability which generates an excessive DC displacement ("coil jump out effect") above resonance frequency.

The time varying properties of the suspension are caused by reversible processes such as the viscoelastic behavior of the suspension. The temporary decrease of the stiffness after large peak displacement recovers slowly after removing the stimulus. The stiffness also varies with the ambient temperature, humidity of the air and the absorbed moisture in the suspension material.

Non-reversible changes which can be interpreted as an "aging" of the suspension have the following causes:

- Initial exposure to mechanical load opens some bonded joints in the impregnated fiber structure (break-in effect).
- Accumulated mechanical load causes slowly growing cracks, destruction of the micro-fibres and other mechanical deformations (fatigue).
- High ambient temperature or voice coil heating changes the suspension properties permanently.
- Humidity, direct water contact and reaction with other chemicals change the material properties.
- Gravity changes the geometry of the suspension part and the coil's rest position if the loudspeaker is mounted in horizontal position.
- Instability of the chemical compounds causes decomposition over time.
- UV light promotes chemical reactions and decay processes in diaphragms and surrounds.

This paper focused on the load-induced aging effects such as break-in and fatigue which important issue for the long-term stability of loudspeaker suspensions.

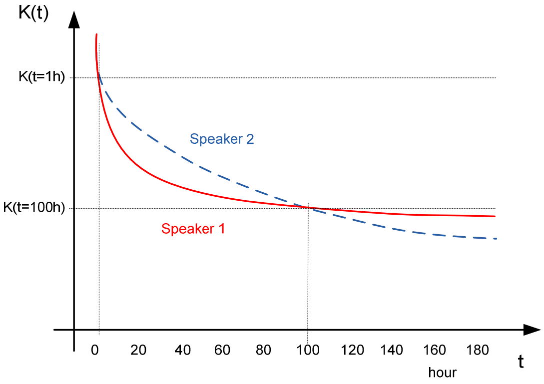

Fig. 1. Variation of the stiffness $K(t)$ of the mechanical suspension of two loudspeakers

versus time t while applying a stimulus of constant amplitude in a power test.

These effects cause significant differences in the aging characteristic as illustrated in Fig. 1 where speaker 1 showed a stronger break-in effect but a lower fatigue than speaker 2.

Some manufacturers as reported in [1] assess the long-term variation

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

by referring the stiffness $K(t=100\text{ h})$ after a 100 hour power test to the stiffness value $K(t=1\mathrm{h})$ after 1 hour of testing when most of the break-in is finished. Although the simple characteristic in Eq. (1) gives some valuable information about the fatigue process it does not consider the late variation in speaker 2 occurring after 100 hours of testing. This number also depends on the amplitude and the spectral properties of the particular stimulus used in the power test.

It is the target of this paper to develop a model describing the aging process for any kind of stimulus and a new measurement technique for identifying the free model parameters. Practical experiments are required to verify the new technique on suspension parts and complete loudspeaker systems. The interpretation of the practical results will be discussed in detail to derive new characteristics which describe the quality of the suspension system and to select optimal components and materials for design and manufacturing.

1.1. Symbols

$a(W)$	instantaneous aging ratio
$Bl(x)$	nonlinear force factor
$C_i, C_{k,i}$	coefficients describing the stiffness losses in the aging models
$F_\mathrm{k}(t)$	restoring force at the mechanical suspension
i_k	current representing the restoring force of the suspension
$K(x,t)$	measured stiffness of the mechanical suspension
$\hat{K}(W)$	predicted mechanical stiffness
K_nom	nominal stiffness of the suspension after break-in
K_∞	final stiffness at the end of the aging process
$P(t)$	apparent mechanical power
$\overline{P}(t)$	mean value of the mechanical power P
P_j	power threshold in multiple-state model
$pdf(P)$	probability function of power P
$R_{100\,\mathrm{h}}$	stiffness ratio after 100 h power testing
R_e	electrical dc voice coil resistance
R_b	break-in ratio
T	integration interval for calculating $\overline{P}(t)$
u_emf	voltage representing velocity of the suspension
$v(t)$	voice coil velocity
V_a	total aging loss of stiffness
V_f	total fatigue loss of stiffness
$x(t)$	voice coil displacement
$w_i, w_{j,i}$	energy constants describing the dynamics of the aging models
$W(t)$	mechanical apparent work
$W_j(t)$	mechanical work accumulated at power $P<P_k$
$W_{50\%}$	mechanical work at aging ratio a=50 %
$W_{90\%}$	mechanical work at aging ratio a=90 %
W_a	mechanical work of the suspension in audio application
Z_L	electrical impedance representing para-inductance of the voice coil

2. MODELING LOAD INDUCED AGING

In this chapter an empirical model of the aging process shall be developed which describes the variation of the stiffness K from a macroscopic view as an analytical function of the mechanical load accumulated during life time cycle. The analytical expression should be intuitive and simple using physical state variables (e.g. displacement x) which are easily accessible by non-destructive testing. Furthermore, the model shall comprise a minimal number of free parameters which have a physical meaning and make a prediction of the final stiffness and the quality assessment of suspension system possible.

2.1. Previous Research

Although break-in and fatigue effects of loudspeaker suspensions are well known phenomena reported in many papers such as in [1] and [3], this issue has never been investigated in greater detail by loudspeaker research. In material science, however, there are plenty of activities on the fatigue of metals, elastomers such as rubber, impregnated glass fibers and other compounds to investigate the nucleation and growth of cracks and to predict the final break of the material [4-11]. The *SN*-curve developed by Wöhler [4] shows the cyclic stress amplitude (S) versus the logarithm of number of cycles (N) required for breaking a clamped sample of the material under sinusoidal excitation. This monotonically falling curve is the basis for calculating the probability of a failure for an arbitrary load using the spectrum of sinusoidal stress components called *fatigue damage spectrum* by *rainflow analysis* and combining the individual contribution at each cyclic stress value by Miner's rule [4]. Although this technique has proved its value for predicting breaks in many materials [12] it cannot explain the break-in effect and the special fatigue symptoms found in a loudspeaker suspension. A complete fission of the spider or surround only occurs under severe overload conditions because the stress at any point on the geometry is usually far below the critical value. However, the microscopic view of material science reveals some interesting points which are also relevant for the macroscopic model developed here for loudspeaker suspensions. The load-induced variation of the stiffness should depend 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 of an alternating stimulus,
- accumulation of the total power transferred to the suspension part during life time of the suspension.

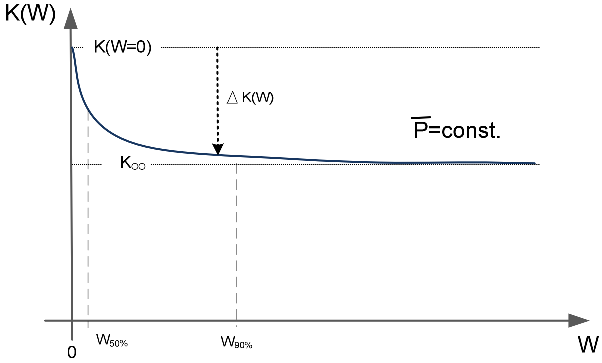

Fig. 2. Stiffness $K(W_\mathrm{k})$ versus accumulated work W measured at constant mechanical power $\overline{P}$

2.2. Mechanical Load

Using this information we describe the mechanical load as the apparent mechanical power

$$P(t) = \left|F_\mathrm{k}(t)v(t)\right| \tag{2}$$

which is the absolute value of the product of restoring force $F_\mathrm{k}(t)$ and velocity $v(t)$. This value changes the potential energy and heat dissipation in the suspension and considers the nonlinear stiffness $K(x)$ generating an increase of the restoring force at high peak displacement $x(t)$. For a sinusoidal excitation with constant peak displacement $x(t)$ the apparent mechanical power rises with frequency f.

2.3. Constant Load Model

At the beginning we develop a relatively simple dosage model which is adequate for long-term testing of suspension parts or for power testing of just assembled loudspeaker systems operated at a constant load defined by the mean value of the apparent power

$$\overline{P}(t_\mathrm{m}) = \frac{1}{T}\int_{t_\mathrm{m}}^{t_\mathrm{m}+T} P(t)dt \approx const. \tag{3}$$

over the interval T.

Fig. 2 shows the variation of the stiffness $K(x{=}0,\ W)$ measured at the voice coil rest position $x{=}0$ as a function of the accumulated work

$$W(t_\mathrm{m}) = \int_0^{t_\mathrm{m}} P(t)dt = \overline{P}t_\mathrm{m}. \tag{4}$$

The curve shape in Fig. 2 is very similar to the curves presented in Fig. 1 because the accumulated work $W(t_m)$ is proportional to the measurement time t_m in those tests because P(t) is approximately constant in those power tests. The instantaneous stiffness

$$\hat{K}(x=0,W) = K(x=0,W=0) - \Delta K(W) \tag{5}$$

can be predicted by using the stiffness variation

$$\Delta K(W) = \sum_{i=1}^{N} C_i\left(1 - e^{-W/w_i}\right) \tag{6}$$

with the free model parameters C_i and w_i and a constraint $w_1 < w_2 < \ldots < w_i < \ldots < w_N$ ensuring uniqueness of the representation. Two exponential functions (N=2) usually give a good fitting of the measured data as discussed in detail below.

2.3.1. Interpretation of the Parameters

The free parameters of the constant load model are easy interpretable and support the quality assessment of suspension parts.

The progress of the load-induced aging can be described by a relative aging ratio

$$a(W) = \frac{K(W=0) - K(W)}{\sum_{i=1}^{N} C_i} 100\ \% \tag{7}$$

which approaches 100 % for an infinite amount of work W. This characteristic is the basis for defining implicitly in

$$\begin{aligned} a(W_{50\%}) &= 50\% \\ a(W_{90\%}) &= 90\% \end{aligned} \tag{8}$$

the amounts of mechanical work $W_{50\%}$ and $W_{90\%}$ required to complete 50% and 90 % of the aging process, respectively. These absolute characteristics expressed in kWh can directly be compared with the work dosage

$$W_{\mathrm{a}} \approx t_{\mathrm{a}} x_{\max}^{2} \pi f_{0} K(x=0) \tag{9}$$

as expected in the particular audio application assuming a sinusoidal excitation over operation time t_{a} at frequency f_0 and a peak displacement $x_{\max}$. Clearly a low frequency tone needs a larger operation time than a high frequency tone of the same displacement to supply the same amount of work to the suspension part.

After applying an infinite amount of work W the final value of the stiffness at the end of the aging process can be predicted by

$$\hat{K}(W \to \infty) = \hat{K}_{\infty} = K(0) - \sum_{i=1}^{N} C_i. \tag{10}$$

The sum of the coefficients C_i referred to the initial stiffness $K(W=0)$ gives a further useful characteristic

$$V_{\mathrm{a}} = \frac{\sum_{i=1}^{N} C_i}{K(W=0)} 100\% \tag{11}$$

describing the relative loss of stiffness over the complete life-time of the suspension part.

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.

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

The break-in ratio

$$R_{\mathrm{b}} = \frac{C_1}{C_1 + C_2} 100\% \qquad \big| N = 2 \tag{12}$$

describes the relative contribution of the break-in effect referred to the total loss of stiffness during aging.

A further important characteristic is the total fatigue loss of stiffness

$$V_{\mathrm{f}} = \frac{C_2}{K(W=0)} 100\% \qquad \big| N = 2 \quad . \tag{13}$$

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

Criteria	Optimal value	Priority
Minimal fatigue	$V_{\mathrm{f}} = 0\%$	1
Dominant break-in	$R_{\mathrm{b}} = 100\ \%$ $W_{90\%} \approx 3W_{50\%}$	2
Slow fatigue process	$w_2 > W_{\mathrm{a}}$	3
Total aging ratio	$V_{\mathrm{a}} = 0\%$	4
Fast break-in process	$w_1 << W_{\mathrm{a}}$	5

Table 1: Criteria important for quality assessment of suspension parts

Table 1 gives an overview on the criteria which are important for ensuring the desired properties of the suspension part over life time. A low fatigue ratio V_f is the most desired property to keep the misalignment of the loudspeaker system in the final application minimal. Suspension parts with a high value of R_b have a dominant break-in effect and the stiffness

$$K_{\mathrm{nom}} = K(W=0) - C_1 \qquad \big| N = 2 \tag{14}$$

after break-in can be used as a nominal value for designing transducers according to desired specifications. The initial misalignment during break-in is acceptable in most audio applications because the dosage (related to parameter w_1) required to pass the break-in phase is small. If the fatigue ratio V_{f} cannot be further reduced it is at least desirable to have a slow fatigue process and a parameter w_2 which is large compared to the work W_{a} expected in the final audio application. The total aging ratio V_{a} has a low priority for quality assessment because it considers break-in and fatigue effects in the same way. Finally it would be desirable to keep the parameter w_1 as small as possible to ensure a short break-in phase.

2.4. Varying Load Model

The dosage model given by Eq. (5) assumes that the aging process is independent on the power value P. However, Fig. 3 shows the aging process of four suspensions of the same type each operated at a different load P_j which was held constant during the test.

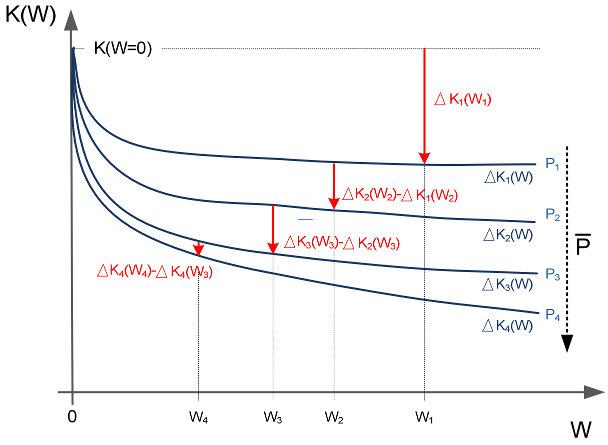

Fig. 3. A set of ageing functions $K(W_j)$ measured at constant mechanical power P_j

Although the curves $K_j(W)$ with j=1,..,4 have a similar shape the stiffness reduces for a higher value of power P_j supplied to the suspension during the test. Therefore, each aging curve $K_j(W)$ requires a separate state variable and Eq. (6) is replaced by a set of equations

$$\Delta K_j(W_j) = \sum_{i=1}^{N} C_{j,i}\left(1-e^{-W_k / w_{k,i}}\right) \quad \left| \begin{array}{l} \overline{P} = P_j = const \\ j=1,\ldots,J \end{array} \right. \tag{15}$$

providing a parameter set for each test at load P_j.
For a sufficient number J of test at equally-spaced power values P_j the measurement results are the basis for predicting the stiffness variation

$$\begin{aligned} \hat{K}(W) &= K(W=0) \\ &\quad -\sum_{j=2}^{J}\left(\Delta K_j\left(W_j\right)-\Delta K_{j-1}\left(W_j\right)\right)-\Delta K_1\left(W_1\right) \end{aligned} \tag{16}$$

versus time t for any load profile $P(t) \neq const.$ as illustrated in the upper diagram in Fig. 4. Eq. (16) uses in contrast to Eq. (5) multiple states

$$W_j(t_0) = \int_0^{t_0} g_j(t)P(t)dt \qquad j=1,\ldots,J \tag{17}$$

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

accumulating the power $P(t)$ above the power value P_j using the window function $g_j(t)$.

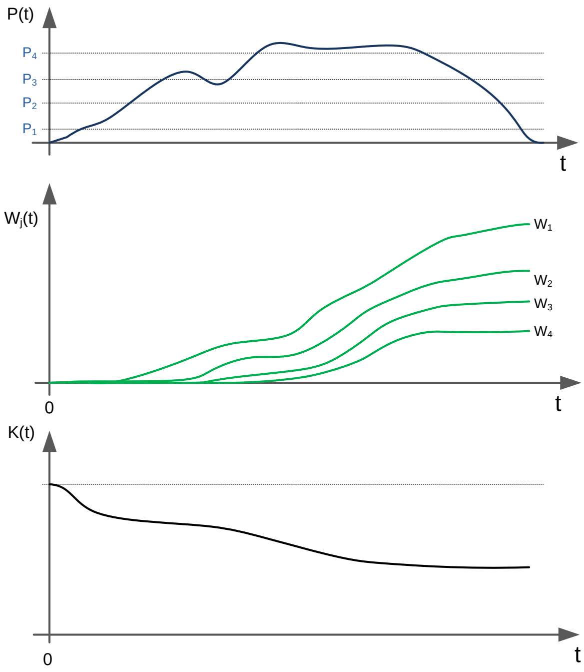

Fig. 4. Prediction of the stiffness variation based on the multiple state model and measured parameters.

The diagram in the middle of Fig. 4 shows that the first state variable W_1 collects almost the complete power $P(t)$ supplied to the suspension while the state variable W_4 accumulates only high power values exceeding the threshold P_4.
The lower diagram in Fig. 4 shows the final stiffness $K(t)$ calculated by summing up the stiffness differences of adjacent dosage models at state variable W_j according Eq. (16) as illustrated in Fig. 3.
Alternatively the accumulated work of each load class P_j can be calculated by

$$W_j = \int_0^{P_j} pdf(P)PdP \qquad j=1,\ldots,J \tag{18}$$

using the probability density function $pdf(P)$ of the apparent mechanical power $P(t)$ which may be derived from the $pdf(x)$ and the power spectrum $S_{xx}(f)$ of the voice coil displacement x and nonlinear stiffness characteristic $K(x)$.

3. MEASUREMENT

To verify the theory developed in the previous chapter a suitable measurement technique has to be developed which is capable of testing suspension parts, transducers and complete loudspeaker systems. This technique should use cost-effective sensors which are operable in hostile environments as commonly used for power testing.

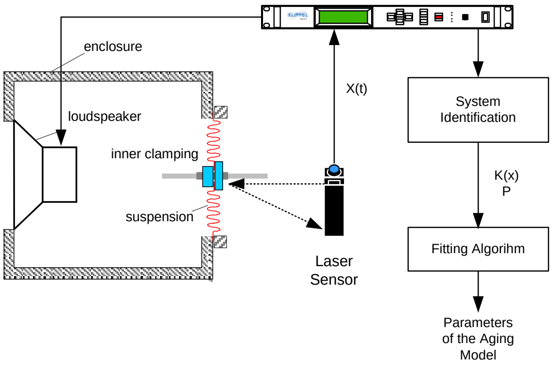

Fig. 5. Measurement of spiders, surrounds and passive radiators using a laser sensor and system identification

3.1. Suspension Parts

There is strong interest in measuring soft parts such as spiders, surrounds and diaphragms before they are assembled. A non-destructive technique for measuring the linear parameters such as the stiffness value $K(x=0)$ and loss factor Q and the nonlinear stiffness characteristic dynamically is recommended by IEC standard [13]. The suspension part is clamped in a sealed enclosure as shown in Fig. 5 and excited by a sinusoidal sound pressure generated by a loudspeaker mounted in the enclosure. A laser monitors the displacement x at resonance corresponding to the mass of the inner clamping part and the stiffness of the suspension. System identification techniques [14] can be used to identify the nonlinear stiffness characteristic $K(x)$ versus displacement x and the apparent power calculated by

$$P(t)=\left|K(x)x(t)\frac{dx(t)}{dt}\right| . \qquad (19)$$

3.2. Electro-dynamical Transducers

The suspension system in an assembled transducer can be simply measured by monitoring electrical signals such as voltage and current at the loudspeaker terminals as illustrated in Fig. 6.

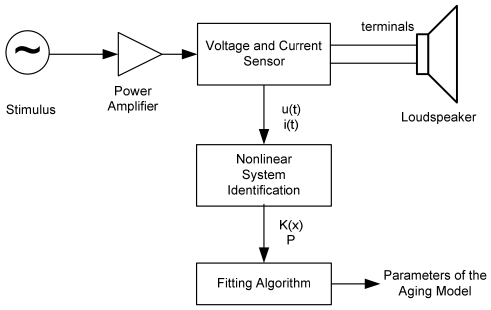

Fig. 6. System identification based on voltage and current signals measured at the loudspeaker terminals.

The apparent mechanical power

$$\begin{aligned} P(t) &= \left|F_k(x)v(t)\right| = \left|K(x)x(t)v(t)\right| \\ &= \left|\frac{K(x)}{Bl(x)}x(t)Bl(x)v(t)\right| \\ &= \left|i_k(t)u_{emf}(t)\right| \end{aligned} \qquad (20)$$

corresponds to the electrical power calculated by the electrical current $i_k(t)$ representing the restoring force $F_k(x)$ of the suspension and the voltage U_{emf} representing the back EMF generated by the velocity $v(t)$ as shown in the equivalent circuit Fig. 7.

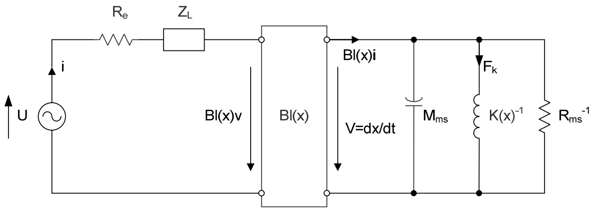

Fig. 7. Electro-mechanical equivalent circuit of the loudspeaker system

The nonlinear force factor characteristic $Bl(x)$ has to be considered in the calculation as a relative quantity. Both, electrical signals $i_k(t)$ and $u_{emf}(t)$ can be determined by nonlinear system identification [15]. This technique requires minimal equipment and is capable of measuring the linear and nonlinear parameters while the loudspeaker reproduces an ordinary audio signal. Neither information about the mechanical system (state variables, parameters) nor an additional sensor (laser or microphone) are required.

3.3. Long-term Monitoring

Nonlinear system identification techniques as developed for power tests (e.g. PWT [16]) and suspension part measurements (e.g. SPM [16]) can be used for *on-line* *monitoring* of the instantaneous stiffness $K(x)$ and other parameters in the small and large signal domain while recording the mechanical load expressed as the apparent power $P(t)$ over measurement time t. This long-term testing commonly known as *power test* reveals loudspeaker properties which are significantly different from the behavior of the cold driver measured without any mechanical pre-excitation in the small signal domain.

To consider voice coil heating and visco-elasticity [3] and to improve the comparability with traditional small signal measurements the long-term monitoring of stiffness and T/S parameters can be realized by additional *intermittent tests* performed at defined intervals (< 6 hours). Here the large signal stimulus is removed and a linear parameter measurement (e.g. LPM [16]) with a small amplitude stimulus is executed after giving the device under test sufficient time (> 30 minutes) to adjust to the ambient temperature and to recover from creep.

The sequence of the measurements is repeated automatically and results of each individual measurement are stored in a database as illustrated in Fig. 8.

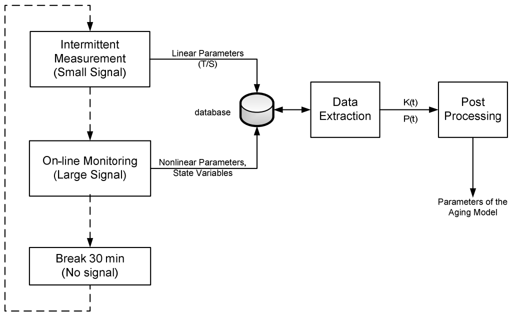

Fig. 8. Long-term monitoring by looping a sequence of measurements and post-processing of the collected data.

The long-term monitoring of the aging process is usually performed on multiple units of the same type which are taken from the same production batch and have never been used before. To generate input data for the fitting of the varying load model the units are operated at different amplitudes (e.g. terminal voltage) which are constant during test and sample the useable working range in 3dB intervals.

3.4. Model Fitting

An extraction tool is used to derive relevant information such as the stiffness $K(t_m)$ and power $P(t_m)$ versus measurement time t_m and to calculate the accumulated work $W(t_m)$ and to estimate the free parameters of the constant load model according to Eq. (5) for each device by minimizing the cost function

$$C=\sum_{m=1}^{M}\left(K(W(t_m))-\hat{K}(W(t_m))\right)^2 \rightarrow \min. \qquad (21)$$

4. PRACTICAL DIAGNOSTICS

A spider having an inner and outer diameter of 39 and 130 mm, respectively, excited by the Suspension Part Measurement (SPM [16]) performs a sinusoidal vibration of 11 mm peak displacement for 250 hours. This corresponds with a constant mechanical apparent power of 2 Watts approximately supplied to the suspension part during the test. Fig. 9 shows the stiffness $K(x=0)$ at the rest position $x=0$ measured in the large-signal domain by on-line monitoring versus the accumulated work W.

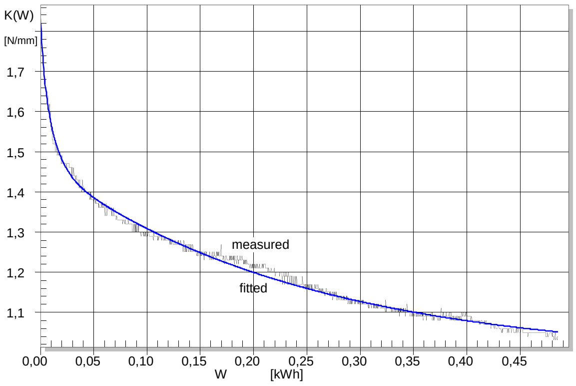

Fig. 9. Measured (thin line) and modeled variation (thick line) of the stiffness $K(x=0)$ at the rest position $x=0$ versus mechanical work W accumulated in a suspension part.

Half of the initial stiffness ($V_a \approx 50\%$) will disappear during the life-cycle of the suspension part. Unfortunately, only half of the changes ($R_b \approx 50\ \%$) occur during the relative short break-in process requiring only $w_1 = 0.02$ kWh. The high fatigue ratio of $V_f \approx 22\ \%$ causes a permanent but slow decay of the stiffness later. This process approaches 90 percent of the final value $\hat{K}_\infty$=0.9 N/mm after applying a high value of the accumulated work $W_{90\%} = 0.42$ kWh $\approx 11 W_{50\%}$. This suspension part does not provide sufficient long-term stability for many applications.

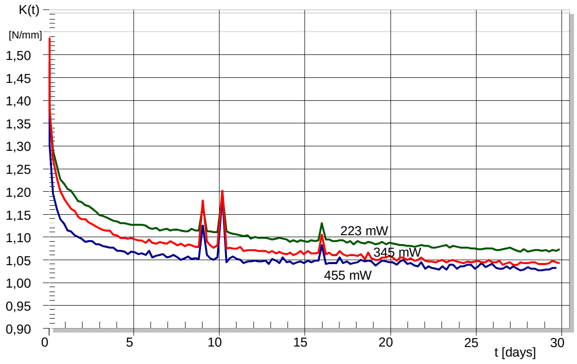

Fig. 10. Mechanical Stiffness $K(t)$ versus time t of three loudspeakers of type A operated at different load P

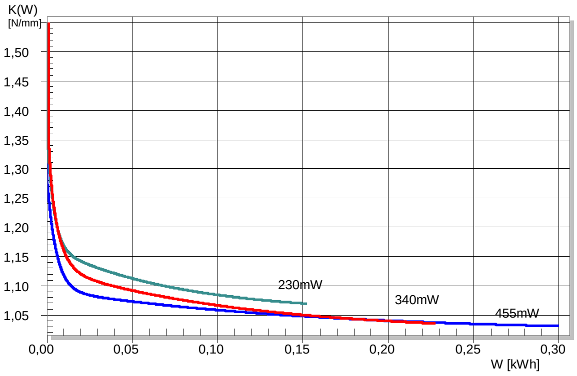

Fig. 11. Predicted stiffness $K(W)$ versus accumulated work W of three loudspeakers of type A operated at different load P calculated from the data in Fig. 10.

The mechanical suspension of loudspeaker A as shown in Fig. 10 and Fig. 11 provides a smaller aging ratio ($V_a \approx 30$ %) and more stability. Most of the variations ($R_b \approx 85$ %) occur during the dominant break-in process and a small amount of work $W_{90\%} \approx 0.1$ kWh is required to approach 90 % of the final stiffness value. This test has been performed on three units taken from the same batch and operated at three different loads during the aging test. Although the curves are very similar there is a small tendency that the aging is increased and accelerated at higher power values P.

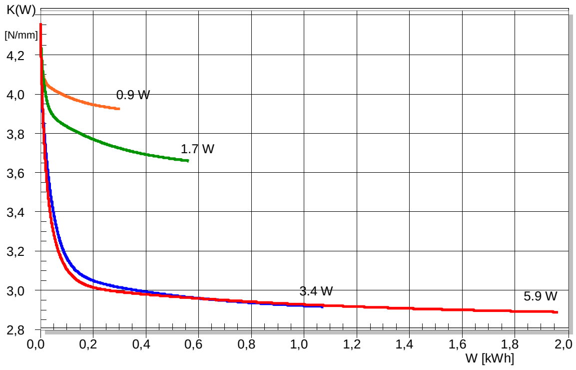

Fig. 12. Mechanical Stiffness K(W) versus accumulated work W of four loudspeakers of type B operated at different load P

The measurements on four units of loudspeaker type B Fig. 12 show that the stiffness $K(W,P)$ is not only a unction of the accumulated work W but also depends to certain degree on the power value P. The two units perated at small power values perform a much slower ging characteristic and will approach a higher finite alue than the other 2 units operated at higher power alues. The similar behavior of the two units operated at .4 and 5.9 W may be caused by a similar peak isplacement limited by the force factor nonlinearity 18].

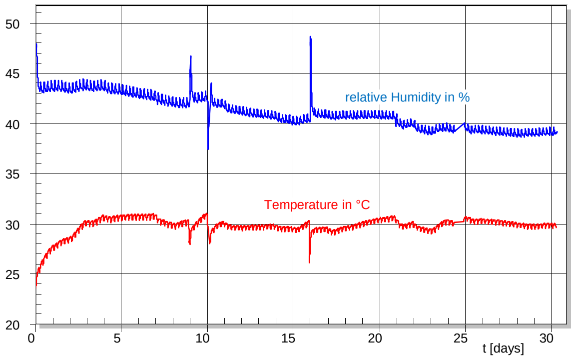

Fig. 13. Ambient temperature T_{amb} and relative humidity versus time t during measurement of loudspeaker A.

5. INFLUENCE OF AMBIENT CONDITION

Ambient temperature and humidity of the air have also a significant influence on the stiffness of the suspension and may cause a significant error in the estimated parameters of the aging model. Fig. 13, for example, shows the temperature and humidity also monitored during the aging test of loudspeaker A. There are significant changes on the 9th, 10th and 16th day causing temporary variations of 5% in the stiffness of all units in the measurement room as revealed as temporary peaks in Fig. 10. It is recommended to perform aging tests under constant ambient condition and to exclude erroneous data points from the fitting of the aging model.

6. CONCLUSION

The load-induced aging of the suspension can be described by a dosage model using the mechanical apparent power as a state variable and a few model parameters. This model considers the velocity and force of the nonlinear vibration generated by an arbitrary stimulus. The free parameters can be easily calculated from results of power tests and other long-term measurements using the recorded stiffness $K(t)$ and apparent power $P(t)$ versus measurement time t. Additional on-line monitoring of the voice coil temperature, displacement, ambient temperature and humidity of the air are required to explain temporary changes of the stiffness caused by varying ambient condition, voice coil heating [17], creep and other visco-elastic effects. Intermittent measurements performed at low amplitudes require an additional break and muting of the high amplitude stimulus for accelerating the aging process to give the suspension part sufficient time to find a thermal and mechanical equilibrium and to produce data which are comparable with the results of traditional small signal measurements. Aging tests applied to loudspeaker transducers require voltage and current monitoring only and can be easily performed on multiple units taken from the same loudspeaker batch to increase accuracy and to investigate the influence of the power level P.

The model has been verified on a variety of suspension parts and loudspeaker drive units showing a good agreement between measured and predicted stiffness. For most practical applications it is sufficient to perform the aging tests at a constant power level P which is typical for the final application and to use constant load model in Eq. (5) with N=2. The model parameters can be used for predicting the final stiffness value $\hat{K}_\infty$ and for assessing the intensity and dynamics of the aging process. The model supports the separation of the break-in and fatigue effects which is important for assessing the quality and stability of a suspension part. Since break-in is a temporary phenomenon requiring a small amount of mechanical work expressed by parameter w_1 for N=2 the stiffness K_{nom} found after break-in and easily calculated by (14) is a more useful nominal characteristic for loudspeaker design than the initial stiffness $K(W=0)$.

A second important quality criterion is the long-term stability of the suspension which corresponds to a low fatigue loss of stiffness V_{f} expressed by Eq. (13).

This model developed here has been applied to the stiffness value provided by small signal intermittent testing and to the stiffness value at the rest position $x=0$ in the nonlinear stiffness characteristic $K(x)$ provided by on-line monitoring. First experiments revealed that other points in the nonlinear stiffness characteristic, especially at high excursions, are more stable and show a slower aging than the rest position. Further research is required to address the interaction with nonlinear and visco-elastic aspects and to model the influence of the ambient temperature, humidity on the properties of the suspension.

The new empirical model and the measurement technique developed in this paper are the basis for assessing the quality of the suspension parts from a macroscopic perspective. Further research activities on alternative materials and new processing techniques are required to provide new kinds of suspension systems giving the desired linear or nonlinear characteristic and sufficient long-term stability at low manufacturing costs.

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