CHARACTERIZING REVERSIBLE AND IRREVERSIBLE STIFFNESS DEGRADATION IN LOUDSPEAKER SUSPENSIONS

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Abstract

Electrodynamic loudspeaker suspension stiffness degrades over time, altering resonance frequency and compromising long term reliability. The aim of this paper is to characterize stiffness evolution during loading and recovery phases to isolate specific degradation mechanisms. An automated measurement system applies a continuous 20 Hz sine wave to induce high excursion, monitoring applied mechanical work and extracting resonance frequency via the circle fit method on impedance data. A two exponential model characterizes stiffness loss as a function of cumulative work, capturing rapid initial break-in and gradual mechanical fatigue. Subsequently, a time dependent two exponential model describes stiffness recovery during rest periods. Equating the loss and recovery models at the load-recovery transition establishes a mathematical relationship that successfully decouples reversible viscoelastic effects (creep and the Payne effect) from irreversible structural damage (break-in and fatigue). Estimating coefficients from the recovery model isolates purely reversible behavior, allowing for the direct calculation of permanent stiffness loss. Separating the mechanisms prevents temporary viscoelastic variations from obscuring actual structural fatigue, providing critical insight into permanent suspension degradation and improving the accuracy of future loudspeaker durability testing.

Keywords: *Loudspeaker suspension, Stiffness degradation, Viscoelasticity, Mechanical fatigue*

1. Introduction

The suspension of an electrodynamic loudspeaker comprises two components: the surround (Figure 1a), usually rubber or woven fabric, connecting the cone and basket, and the damper or spider (Figure 1b), woven fabric impregnated with resin, connecting the coil former to the basket and acting as the primary stiffness source. The suspension controls moving assembly motion by providing a stiffness based restoring force and aligning the assembly on the coil former's axis.

(a) Surround   **(b)** Damper

Figure 1: Loudspeaker suspension components: (a) surround and (b) damper.

Suspension properties change over time due to load and environmental factors. Creep (deformation under load) and the Payne effect (stiffness change versus displacement) are reversible viscoelastic processes. Conversely, aging or fatigue represents irreversible stiffness loss under long term load [1]. Deformation and aging impact the behaviour of electrodynamic loudspeakers by causing:

- decreased resonant frequency (For example, break-in causes a significant initial stiffness drop during the first hours of excitation as microscopic resin bridges in the fabric fracture [1]),
- shifted coil rest position and altered centering,
- increased risk of bottoming (coil striking the motor),
- altered harmonic distortion behavior.

In the present work, a set of automated measurements is used to monitor changes over time in the stiffness of the suspensions of various loudspeakers at different excitation levels, in order to assess the aging and changes in the viscoelastic properties of these suspensions. The suspension stiffness evolution is thus

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investigated as a function of time and accumulated mechanical work.

The article first reviews loudspeaker suspension components and details the applied measurement methodology. Next, mathematical models for work dependent stiffness loss and time dependent recovery are introduced. Finally, correlating the two models isolates reversible viscoelastic effects from permanent structural damage.

2. Previous Art

From a theoretical point of view, the moving part of a loudspeaker is usually modeled as an ideal linear damped oscillator involving a moving mass M_m $[kg]$, a mechanical compliance C_m $[mm.N^{-1}]$ (stiffness inverse), and a mechanical resistance R_m $[N.s.m^{-1}]$. However, viscoelastic properties have also to be taken into account [2]. Indeed, suspension compliance increases at high displacement as it is stretched, altering the speaker resonance frequency during operation. In the Standard Linear Solid (SLS) model, the suspension is represented by an elastic spring in series with a parallel spring-dashpot combination. This model can be used to effectively describe viscoelastic effects by combining Maxwell and Kelvin-Voigt models [3]. Alternatively, Klippel [1] models the evolution of the suspension stiffness as a function of cumulative mechanical work experienced by the loudspeaker moving part. This model is used in Section 4 to describe stiffness degradation.

From an experimental point of view, loudspeaker suspensions can be characterised in various ways. Commercially available measurement benches can extract suspension parameters. For example, the Klippel Loudspeaker Suspension Testing (LST) bench [4], [5] clamps the damper or surround atop a box, utilizing a bottom mounted loudspeaker for excitation and a laser to measure displacement versus frequency. Extracted parameters include stiffness (K_m), resonant frequency (f_r), and quality factor (Q). A simpler static setup can also be used which involves hanging a known mass from the damper and measuring deformation. This method requires less equipment but mandates extended wait times to ensure stabilization. Both techniques are primarily used to verify manufacturer batch specifications. Alternatively, Klippel Large Signal Identification (LSI) measures nonlinear mechanical parameters. LSI requires an assembled driver and captures the combined stiffness of the damper and surround, rather than isolated components.

3. Testing Procedure

This work aims to characterize speaker suspension stiffness evolution over time, when it is subjected to prolonged stimulation, and its subsequent recovery, through measurement and modeling. To do this, two sets of measurements are carried out on a loudspeaker. Figure 2 displays the block diagram of the measurement process.

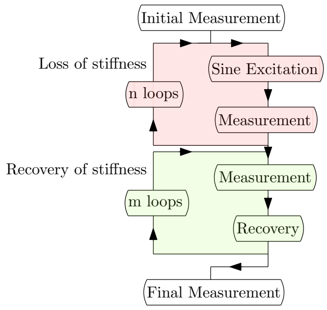

Figure 2: Schematic of the measurement process

Figure 3 displays a schematic of the experimental setup. A laser measures displacement, while voltage and current are measured across the speaker and a 1 Ω resistor.

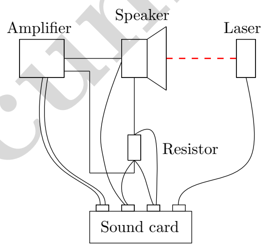

Figure 3: Schematic of the measurement setup

3.1. Stiffness loss versus work

The first set of measurements allows to evaluate the loss of stiffness as a function of the cumulative work experienced by the moving assembly. A 20 Hz sinusoidal voltage is applied to the loudspeaker input for a specified duration, after which the loudspeaker's electrical impedance is measured. This operation is repeated n times. Note that the 20Hz sinusoidal voltage has been chosen as the excitation signal because it maximizes dwell time at high excursions of the membrane. During the sinusoidal excitation phase, the current $i(t)$ and the displacement $x(t)$ of the diaphragm are recorded in order to calculate the work W to which the suspension has been subjected.This cumulative work is given by

$$W = \int P(t)dt, \tag{1}$$

where the power $P(t)$ is given by

$$P(t) = F(t)v(t), \tag{2}$$

where $v(t)$ is the velocity of the membrane and where the force $F(t)$ is the Laplace force,

$$F(t) = Bl\ i(t). \tag{3}$$

Because the force factor Bl varies with displacement ($Bl = Bl(x)$), particularly at high excursion, calculating work requires to know the average force factor (Bl_{av}). A polynomial expression of $Bl(x)$ is obtained beforehand from LSI measurement. Then, by multiplying $Bl(n)$ values at specific position n by corresponding dwell time ($D(n)$) and averaging across x data points yields the average force factor Bl_{av},

$$Bl_{av} = \frac{\sum_{n=0}^{x} Bl(n)D(n)}{x}. \quad (4)$$

Finally the Laplace force is given by

$$F(t) = Bl_{av}\ i(t). \quad (5)$$

After each sinusoidal excitation, a low-voltage (0.1 V) impedance measurement is carried out which yields the resonance frequency (f_r).
To determine the resonance frequency with high precision despite low sampling frequencies and measurement noise, the circle fit method is applied [6], [7], [8]. This method is based on the fact that the complex impedance of a high Q resonator traces a circle in the Nyquist plane near resonance. An initial zero crossing estimate isolates data within a ±5 Hz window, which is then fitted to a geometric circle using the Least Mean Square (LMS) method. Resonance occurs when the impedance is purely resistive. The intersection of the fitted circle with the Real axis ($\Im(Z) = 0$) is calculated by setting $y = 0$ in Eq. (6),

$$(x_{res} - x_c)^2 + (0 - y_c)^2 = R^2. \quad (6)$$

Solving this equation yields the geometric resonance point ($x_{res}, 0$). To recover the frequency information, the spatial angle of each measured point is calculated relative to the circle center. Because frequency varies linearly with the angle along the resonance arc for high Q resonators, a linear regression maps the ideal resonance angle to the continuous resonance frequency f_r.
Knowing the resonance frequency f_r and the moving mass M_m, obtained via Klippel Linear Parameter Measurement (LPM), one can determine the suspension stiffness K_m from the following relation,

$$K_m = (2\pi f_r)^2\, M_m. \quad (7)$$

Then, a new sinusoidal excitation phase is launched and the experimental process is thus repeated n times to monitor the K_m evolution as a function of cumulative work W.

3.2. Recovery of stiffness over time

The second set of measurement is used to monitor the recovery of stiffness over time. The process begins with an impedance measurement to determine the resonance frequency. Then the loudspeaker is left to rest for 15 minutes before the impedance is measured again. This process is repeated m times.

3.3. Results

Figure 4 displays the typical evolution of the resonance frequency f_r during the various stages of the measurement protocol. Resonance frequency exhibits a sharp initial decay during the first hours of testing, followed by a more gradual decline. Recovery follows a similar two stage profile: rapid initial restoration transitioning into a slower convergence. These frequency shifts directly reflect underlying changes in suspension stiffness, as expressed in Eq. (7).

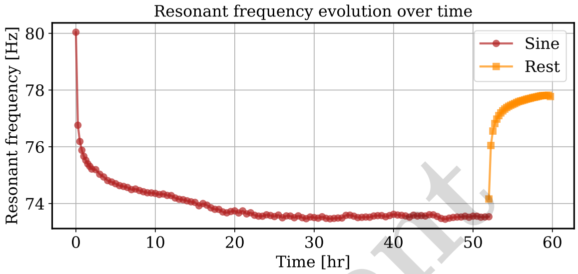

Figure 4: Typical data from a measurement

4. Modeling the Loss of Stiffness

Klippel [1] defines a stiffness loss model as a function of cumulative mechanical work. This model represents the time-dependent evolution of stiffness, from its initial rest position value, as a sum of N decaying exponential functions of mechanical work,

$$\hat{K}_{loss}(W) = K(x=0, W=0) - \sum_{i=1}^{N} C_i \left(1 - e^{-W/w_i}\right), \quad (8)$$

where C_i and w_i are fitting parameters. Note that the values of w_i are constrained by $w_1 < w_2 < \ldots < w_N$ to ensure unique representation.

As shown on Figure 5, only the two first terms of the sum ($N = 2$) are sufficient to provide an accurate fit to the measured data.

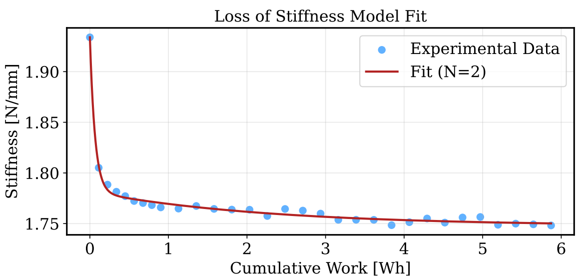

Figure 5: Fit of the loss of stiffness model to the measured data

The first exponential captures the sharp initial decay caused by breaking resin bridges (break-in), creep, and the Payne effect under high displacement. The second exponential captures the gradual decay associated with long term mechanical fatigue. The results shown in Figure 5 are obtained with a 4-inch midrange driver driven by a 4.5 V sine signal. The $N = 2$ model also successfully fits data from a 5-inch Audax HM130G0 and a 2-inch Audax HT080G0.

Extrapolating the model to higher work values predicts the steady state asymptote. Identifying the steady state stiffness at specific excitation levels is crucial for proper speaker enclosure sizing, particularly for ported or passive radiator designs.

5. Modeling the Recovery of Stiffness

The study of the behavior of the suspension is extended here to the recovery phase. Some of the mechanisms that cause the suspension to get more compliant (creep and the Payne effect) are reversible, and after some rest, the speaker regains part or all of its stiffness if no fatigue was induced in the suspension. A two exponential model describes this recovery as a function of time,

$$\hat{K}_{rec}(t) = K(x = 0, W = 0) - \sum_{i=1}^{N=2} A_i e^{-t/\tau_i}, \qquad (9)$$

where the value of stiffness $K(x = 0, W = 0)$ is the original stiffness measured at the beginning of the whole testing procedure, and where A_i and τ_i are fitting parameters. Using the value of the stiffness from the first measurement implies that no damage is caused to the suspension that would make it unable to regain its full stiffness. However, there is always a little bit of aging that is induced during the testing. This causes a loss of accuracy of the model. A way to counter this problem is to consider a different target value $K(x = 0, W = 0)$ that the stiffness converges to. This value is unknown and becomes one of the parameters of the model. It is determined when the model reaches an asymptote.
For example, Figure 6 displays a fit of the model for both fixed original value and fitted value of stiffness, for a 4-inch midrange driver, when minimal aging occurs. Here, the suspension experienced almost no aging, so the fitted stiffness and the original one are very close to each other.

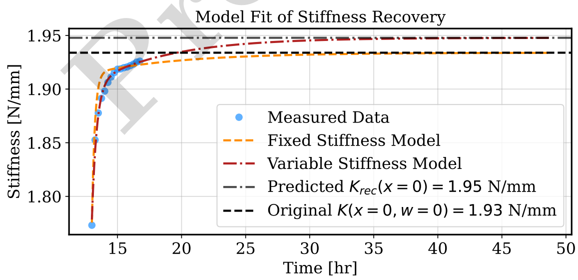

Figure 6: Fit of the recovery of stiffness model to the measured data

Under conditions inducing significant permanent ageing, the model based on original stiffness becomes entirely inaccurate. Indeed, since the suspension has permanently lost part of its stiffness during the loading part of the process, it cannot be expected to return to its original stiffness after some rest. For example, Figure 7 which correspond to a case where the loudspeaker under test has experienced a set of high level voltage sinusoidal excitation (7 V RMS), show that the model based on the original stiffness converges towards non valid results, whereas the model using the fitted stiffness aligns perfectly with the experimental data.

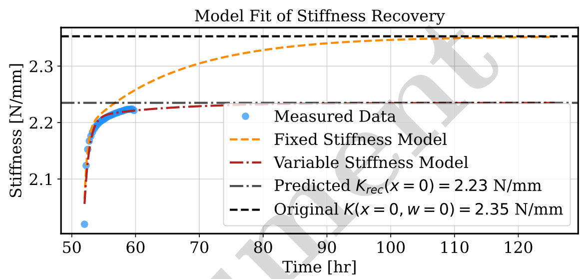

Figure 7: Fit of the recovery of stiffness model to the measured data

6. Determining the Different Mechanisms in the Loss of Stiffness

This section details the relationship between the stiffness loss and recovery models to analyze suspension mechanisms.

6.1. Relation between the Loss and Recovery of Stiffness Models

At the exact transition between loading and recovery phases, the predicted stiffness values from both models are equal, expressed in Eq. (10),

$$\hat{K}_{loss}(W) = \hat{K}_{rec}(t). \qquad (10)$$

Canceling the initial stiffness terms yields Eq. (11), assuming no permanent suspension damage occurs during loading,

$$\sum_{i=1}^{N=2} C_i \left(1 - e^{-W_{final}/w_i}\right) = \sum_{i=1}^{N=2} A_i e^{-t/\tau_i}, \qquad (11)$$

with W_{final} representing the cumulative work at the end of the measurement cycle.

Evaluating at $t = 0$ (the start of recovery) simplifies the time dependent exponentials ($e^0 = 1$), resulting in Eq. (12),

$$A_i = C_i \left(1 - e^{-W_{final}/w_i}\right). \qquad (12)$$

Thus, the values of weights A_i can be estimated from Eq.(12) using the values of C_i and w_i previously obtained by fitting expression (8) to the experimental stiffness loss. Figure 8 shows the theoretical recovery evolution calculated using Eq. (9), where the values of A_i are estimated from Eq. (12) and the parameter τ_i is obtained through fitting.

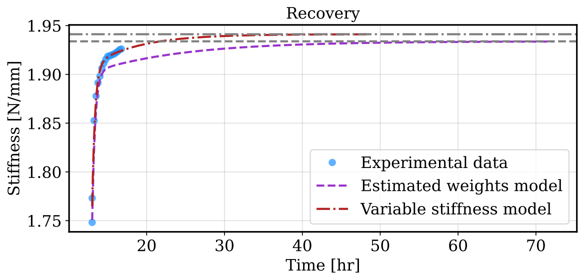

Figure 8: Fit of the stiffness recovery model using interpolated weights to the measured data

The model utilizing estimated weights A_i shows slight deviations in recovered stiffness due to aging during measurement. Discrepancies arise because suspension properties change between the initial loading and recovery phases. For minimal aging, the estimated weights provide an adequate fit. Conversely, significant aging produces large errors, as shown in Figure 9.

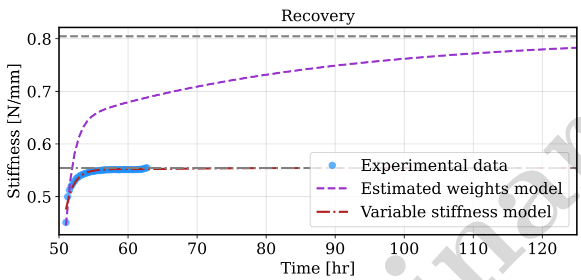

Figure 9: Fit of the stiffness recovery model using interpolated weights to the measured data

The estimated weights model produces large errors when permanent damage prevents a return to the original stiffness.

6.2. Identifying the Different Mechanisms in the Loss of Stiffness

Equation (12) also allows the weights C_i to be estimated in terms of the weights A_i,

$$C_i = \frac{A_i}{1 - e^{-W_{final}/w_i}}. \tag{13}$$

Then, because A_i weights depend solely on reversible viscoelastic processes, the estimated C_i weights represent purely reversible suspension damage. This assumes permanent damage mechanisms (break-in and long term fatigue) leave the model's work constants (w_i) unaffected. Break-in occurs initially and could alter the first work constant w_1, whereas fatigue exhibits a lower slope, minimally impacting the second one w_2. To verify break-in effects on the first work constant, a single driver undergoes multiple measurement cycles. If break-in alters the exponential decay shape, the initial cycle's work constant must differ from subsequent, break-in-free cycles. Figure 10 displays the stiffness data as a function of time for multiple measurement cycles (ignoring multi-day rest gaps) at 6.5 V.

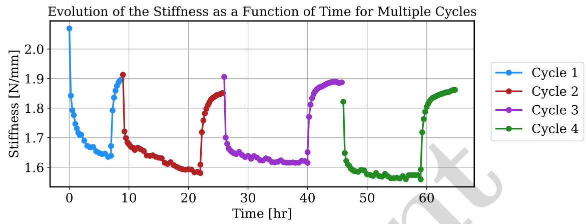

Figure 10: Stiffness data from multiple measurement cycles

Fitting the loss of stiffness model to each cycle yields the first weight constants presented in Table 1. Table 2 displays the first weight constants for a different sample of the same driver type at 5.5 V.

Table 1: Driver type 1, 6.5 V input signal

Cycle	w_1
1	0.11
2	0.11
3	0.09
4	0.12

Table 2: Driver type 1, 5.5 V input signal

Cycle	w_1
1	0.11
2	0.12
3	0.11
4	0.12

Both tables indicate the first weight constant remains unchanged regardless of initial break-in for this specific speaker and input levels. In measurements lacking break-in, the work constant remains stable. Mullins [9] supports this, demonstrating that materials settle into stable stress-strain loops post-break-in; structural bonds break, but the underlying viscoelastic behavior (represented by the work constants) stabilizes.

Because irreversible mechanisms do not affect work constants, calculating the stiffness loss model using coefficients estimated from the recovery model (Eq. (13)) isolates purely reversible viscoelastic behavior. Total stiffness loss comprises the sum of reversible and irreversible mechanisms, as expressed in Eq. (14),

$$K_{total} = K_{viscoel} + K_{irrev}. \tag{14}$$

Figure 11 displays the evolution of the estimated viscoelastic loss and the calculated irreversible contributions, corresponding to the difference between experimental stiffness and estimated viscoelastic one, for a cycle exhibiting negligible permanent damage. In this case, the estimated viscoelastic stiffness shows a strong alignment with experimental data.

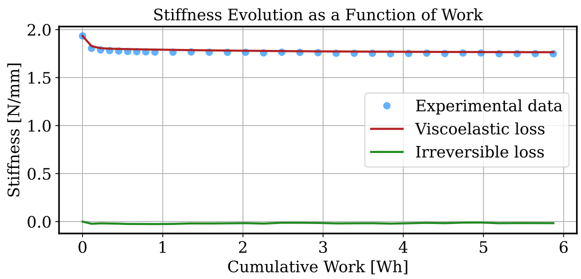

Figure 11: Evolution of the different mechanisms as a function of work

Figure 12 show the sames quantities for a cycle of excitation causing significant irreversible damage.

Figure 12: Evolution of the different mechanisms as a function of work

In this case, the purely viscoelastic model naturally underestimates total stiffness. The extracted irreversible loss curve highlights two permanent degradation phases, an initial sharp decay from break-in, followed by a gradual decline from long-term fatigue.

Separating reversible viscoelastic effects from permanent damage enhances speaker durability testing analysis. Isolating irreversible losses prevents temporary viscoelastic variations from obscuring the evaluation of actual structural fatigue.

7. Conclusion

Measurements across multiple loudspeakers and excitation levels assess suspension stiffness evolution during load and recovery. An automated experimental set-up monitors stiffness, employing the circle fit method to extract resonance frequency.

Applying Klippel's model [1], a two exponential function characterizes stiffness loss versus mechanical work, capturing both the rapid initial decay (break-in and viscoelasticity) and the gradual long term decay (fatigue). This model enables steady state stiffness prediction for any cumulative work volume.

Similarly, a two exponential, time dependent model describes stiffness recovery. This process reflects an initially sharp rebound that converges to an asymptotic value, highlighting the suspension's inherent viscoelastic properties.

Relating these loss and recovery models successfully separates reversible viscoelastic effects (creep and Payne effect) from irreversible structural damage (break-in and fatigue). Decoupling these mechanisms provides critical insight into the root causes of permanent suspension degradation, improving the accuracy of future loudspeaker durability assessments.

References

[1] W. Klippel, "Mechanical fatigue and load-induced aging of loudspeaker suspension," Jan. 2011, KLIPPEL GmbH.

[2] A. Novak, "Measurement of loudspeaker parameters: A pedagogical approach," Sep. 2019, Laboratoire d'Acoustique de l'Université du Mans.

[3] R. Brosch, "Loudspeaker simulation considering suspension creep," Dec. 2020, Institute of Signal Processing and Speech Communication Graz University of Technology.

[4] R. Werner and W. Klippel, "Fast quality testing of loudspeaker suspension parts," Jun. 2007, KLIPPEL GmbH.

[5] W. Klippel and U. Seidel, "Dynamical measurement of loudspeaker suspension parts," Jan. 2012, KLIPPEL GmbH.

[6] D. J. Inman, *Engineering Vibration*, 4th ed. Pearson, 2014, ch. 7, ISBN: 978-0-273-76844-9.

[7] D. J. Ewins, *Modal Testing: Theory, Practice and Application*, 2nd ed. Research Studies Press LTD., 2000, ch. 1 and 2.

[8] J.-C. Le Roux, "Le haut-parleur électrodynamique : Estimation des Paramètres Électroacoustiques aux Basses Fréquences et Modélisation de la Suspension.," Theses, Le Mans Université, Apr. 1994.

[9] L. Mullins, "Softening of rubber by deformation," *Rubber Chemistry and Technology*, vol. 42, no. 1, pp. 339–362, 1969. DOI: 10.5254/1.3539210

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