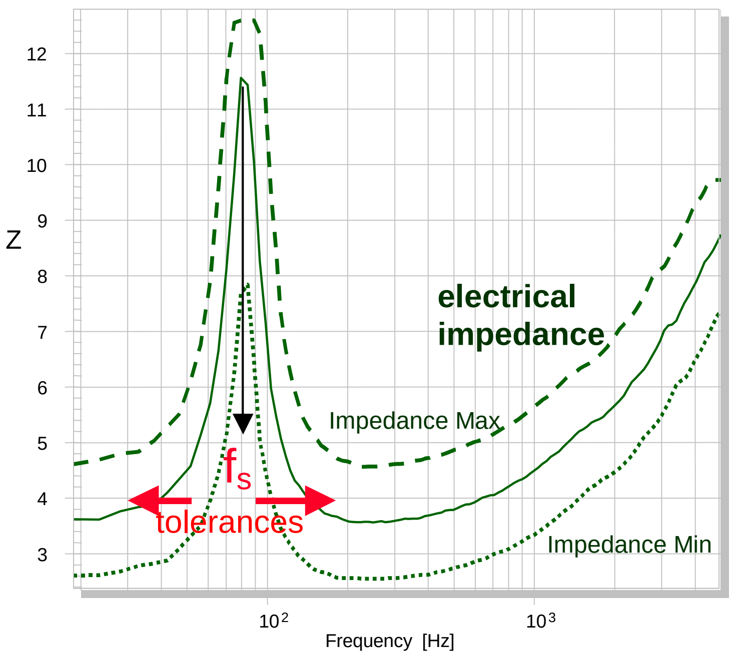
Tolerances of the Resonance Frequency f_s **AN 42**

Application Note to the KLIPPEL R&D SYSTEM

The fundamental resonance frequency f_s is one of the most important lumped parameter of a drive unit. However, the measured value of f_s may vary from unit to unit and may also depend on the measurement conditions. This paper reports from an systematic investigation and a statistical investigation of multiple units of 4 loudspeaker types. The results from an analysis of variances shows that the dominant factors of influence are peak to peak displacement, climate and history of the measurement. The application note gives practical tips how to perform reliable measurements and define meaningful tolerances.



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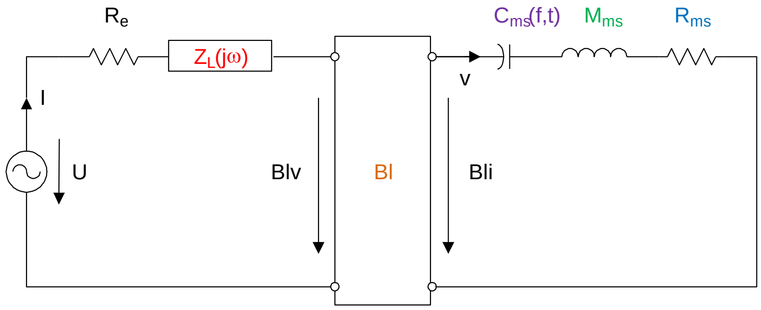
Introduction

Definition

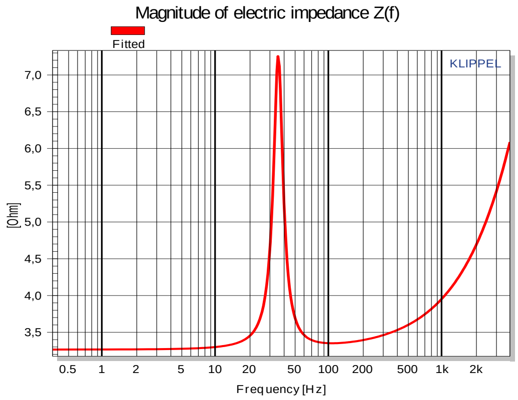


The moving mass Mms and the compliance Cms generate a vibrating system with a resonance frequency

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{C_{ms}M_{ms}}}$$

The suspension parts (spider and surround) and the enclosed air (e.g. below the dust cap) determines the mechanical compliance $C_{ms(t,f)}$. This parameter varies significantly with displacement, time and depends on the ambient conditions (temperature and humidity). The moving mass M_{ms} considers the mass of the moving loudspeaker parts and the air load.

Measurement of the resonance frequency



The maximum in the electrical input impedance Z(f) reveals the fundamental resonance. The fitting of the modeled curve based on the estimated lumped parameters with the measured impedance curve is the most reliable way for estimating the resonance frequency and other small signal parameters.

Diagnostic value

The measurement of the resonance frequency fs is relatively simple and this value shows

- the lower limit of the useable bandwidth of the loudspeaker,
- is directly related with the moving mass M_{ms} which directly determines the sensitivity of the loudspeaker in the pass band,
- is directly related with the compliance C_{ms} of the suspension and with the displacement of the voice coil. Higher compliance may increase the peak displacement below f_s for a given voltage and may generate rub and buzz distortion at high amplitudes.

Measured resonance frequency fs depends on

Suspension parts	Mechanical Compliance C_{ms} of the drive unit depends on the properties of the spider and surround made of impregnated fabric, rubber, foam and other soft materials. *Recommendation:* Measure the compliance of the suspension parts with a dynamic measurement technique as defined in the IEC standard 62459. Fast measurements can be accomplished in the small signal domain by placing a metal cone of known mass in the inner side of the suspension part and by using a pneumatic excitation. Find an agreement of permissible tolerances for the compliance of the suspension part manufacturer and check this on a regular basis.
Climate condition	The properties of suspension parts highly depend on the climate condition (humidity and temperature). If the temperature rises from –100 Celsius (for example cold loudspeaker in a car in Canada in winter) to 400 Celsius (hot loudspeaker in a car in Mexico) the compliance may rise by 200% and the resonance frequency may be one octave lower. *Recommendation:* Therefore the ambient conditions where the device under test is stored or measured should be controlled at least 24 hours before testing. If this is not possible measure humidity and temperature during end-of-line testing and store those data together with the loudspeaker characteristics and makes it possible to explain the major variation of resonance frequency f_s and allow a prediction of the variation based on simple mathematical model (linear regression).
Ageing of the suspension	The properties of the suspension parts vary with time. Operating a suspension at high amplitudes over some time causes an irreversible rise of the compliance C_{ms} which is well known from long-term power testing after “breaking in”. The resonance frequency of a just assembled drive unit may change in the next hours due to the hardening of the glue. *Recommendation:* Golden reference samples taken some time ago may significantly differ from the devices tested at the end of the assembling line. This difference should be considered in the calculation and recalibration of the limits applied to fs.
History	The compliance C_{ms} of the suspension decreases for a short time (a few seconds) after having a larger displacement where the microfibres in the woven fabric have changed their position and the viscous properties of the impregnation delay the relocation process. Thus the pre-stress during a large signal measurement (e.g. rub and buzz and distortion measurement, motor and suspension checks) will affect the measurement of the resonance frequency in the following impedance measurement at low frequencies. *Recommendation:* Perform the small signal measurement before the large signal measurements.

Amplitude of stimulus	The peak to peak displacement generated by the stimulus affects the variation of the resonance frequency. In the small signal domain where the geometrical nonlinearities of the suspension are negligible the resonance frequency decreases with rising amplitude. This effect is closely related to the visco-elastic behavior described in the last factor “History”. In the large signal domain the nonlinearities increase the stiffness and this mechanism increases the resonance frequency eventually. *Recommendation:* Generate the same peak to peak displacement to compare measurements with different stimuli (bandwidth, density of tones, crest factor). The voltage at the loudspeaker terminals is not a sufficient specification to ensure comparable results!
Measurement time	The length of the stimulus used in the impedance measurement affects the variation of the resonance frequency by two ways: a) visco-elastic behavior of the suspension: The longer the measurement the larger is the temporary loss of stiffness. b) Signal to Noise ratio: If the measurement time is very short and the excitation amplitude low the impedance curve is corrupted by measurement noise causing a less accurate estimation of fs in the curve fitting *Recommendation:* There is no time for extensive averaging of the impedance curve during end-of-line testing. If the measurement time is very short (200 ms) the voltage at the terminals should be adjusted carefully to ensure a good signal to noise ratio and to avoid nonlinear distortion.
Waveform of the stimulus	The measured resonance frequency f_s also depends on the spectral and temporal properties of the stimulus: a) Resolution: A poor resolution of the measured impedance curve may produce errors in the fitting algorithm which affects the accuracy of the fs estimation. b) Crest factor: The ratio between peak value and rms value of the voice coil displacement should be low to avoid nonlinear distortion. c) Bandwidth: The resonance should be excited at least one octave below and above the resonance to get precise values for fs. However, the precise measurement of the dc resistance R_e, inductance le, the electrical, mechanical and total Q factors Q_{es}, Q_{ms} and Q_{ts}, respectively, requires sufficient bandwidth from $0.1f_s < f < 10\ f_s$ d) Sweep direction: Sweeping the frequency up or down can also affect the results of the fs measurement. *Recommendation:* Use a stimulus which provides maximal resolution in the measured impedance curve. The sinusoidal sweep with speed profile and the multi-tone stimulus are the most powerful stimuli for measuring the impedance curve at high signal to noise ratio in the shortest time possible. a) The multi-tone complex requires a pre loop to excite the loudspeaker into steady-state condition. The multi-tone stimulus measures the impedance at discrete lines at highest precision and may also monitor the nonlinear distortion in the bins of the FFT spectrum which are not excited by the stimulus. b) The sinusoidal sweep with speed profile requires no pre-excitation and measures the loudspeaker by using a single transient signal. A low sweeping speed about the resonance frequency ensures high resolution here, which is important for a precise measurement of the small signal parameters. Sweeping upwards is recommended for short stimuli (200 ms) because the transient behavior of the loudspeaker at resonance (high group delay) is still recorded during the sweep generates the following high frequency components. Neither time window should be applied to the electrical impulse response nor smoothing should be applied to the impedance response to sustain maximal resolution of the resonance curve.

Moving Mass	Total moving mass Mms is influenced by the weight of the parts and glue used for assembling. *Recommendation:* Measure the mass of the parts on a regular basis.
Calculation method	There are many ways for estimating the resonance frequency: • Searching for the Impedance Maximum • Searching for the zero phase angle in the complex impedance response • Fitting the measured impedance curve to measured curve predicted by lumped parameter model *Recommendation:* Specify the method used. The Fitting technique provides the highest accuracy even if the impedance curve is corrupted by measurement noise.

Report on a practical investigation

Target

Practical measurements and statistical investigations are performed and the most interesting results are reported here. The targets of the investigation were

- to check the reproducibility and repeatability of the measurement technique (example: Klippel R&D System contra KLIPPEL QC System)
- to check the variance of the manufacturing process
- check the influence of the measurement condition on the resonance frequency f_s

Loudspeaker under test

Name	Number of units	Properties
speaker 1	10 units	4" in diameter with neodymium magnet
speaker 2	17 units	4" in diameter with ferrite magnet
speaker 3	12 units	6,5" woofers with 4 Ohm
speaker 4	12 units	6,5" woofers with 8 Ohm

Repeatability of the Measurement

After repeating all tests under identical conditions the intra-individual confidential range has been calculated. The table below shows the result for a test using a multi-tone signal of 0.5s length and a terminal voltage of 0.2 V_{rms}:

	Mean Value **fs** in Hz	**Intra-individual Confidential Interval** of fs in Hz (absolute)	**Intra-individual Confidential Interval (relative)**
speaker 1	110,48	110,37... 110,58	**+-0,24%**
speaker 2	104,62	104,59 ... 104,65	**+- 0,13%**
speaker 3	53,52	53,47 ... 53,57	**+- 0,43%**
speaker 4	59,61	59,53 ... 59,7	**+- 0,53%**

Conclusion: A very small value of the relative intra-individual confidential interval (mean value 0.4%) is found which shows that the resonance frequency f_s can be measured by a short measurement technique.

Comment: As a result of an analysis of variance the **intra**-individual variance is calculated which considers the variation of the resonance frequency of each device while repeating the measurement under identical or systematically changed measurement condition (e.g. varied voltages). The variation of the resonance frequency between units is excluded. The intra-individual confidential interval in percent is calculated by dividing the 2 sigma range by the mean resonance frequency which corresponds with 95% confidential range.

Production consistency

As a result of a analysis of variance the **inter**-individual variance is calculated, which considers the variation of the resonance frequency between the different units under identical measurement condition. The variation of the resonance frequency caused by the measurement condition (e.g. varied voltage) is excluded. The inter-individual confidential interval is calculated by dividing the 2 sigma range by the mean resonance frequency which corresponds with 95% confidential range. If the manufacturing process is very stable the inter-individual confidential range is very small and all units have a similar value of f.

	Mean value fs in Hz	**Inter-individual Confidential Interval of fs in Hz (absolute)**	**Inter-individual Confidential Interval of fs in percent (relative)**
speaker 1	110,48	106,44 ... 114,51	**+- 3,65%**
speaker 2	104,62	103,12 ... 106,12 ;	**+- 1,43%**
speaker 3	53,52	50 ... 57,04 ;	**+- 6,58%**
speaker 4	59,61	55,51 ... 63,71 ;	**+- 6,88%**

Conclusion: The inter-individual confidential interval (mean value **+-** 4.9%) describing the production consistency is about 10 times higher than the intra-individual interval limited by the measurement technique.

Causes for production variances	
	The variation of the resonance frequency f_s between the units are caused by variation of the moving mass M_{ms} and compliance C_{ms}. inter-individual confidential intervals for Mms and C_{ms} of speaker 3 were calculated by using the laser measurement technique of the R&D System and presented in the table below:

Characteristic	**Symbol**	**Inter-individual Confidential Interval (relative)**	**Intra-individual Confidential Interval (relative)**
resonance frequency	f_s	**+- 6,58%**	**+- 0,31%**
Moving mass	M_{ms}	**+- 5,1%**	**+- 1,2%**
Total Compliance	C_{ms}	**+- 13,7%**	**+- 1,5%**

Conclusion: The high value 13.7 % of the inter-individual confidential interval of the C_{ms} shows that the main source of f_s variance is caused by the manufacturing of the suspension parts (spider and surround). The inter-individual confidential interval of the moving mass M_{ms} of 5.1% is much smaller showing that the assembling process (e.g. the glue dispensing system) is much more stable. The low values in the intra-individual confidential interval shows that the laser measurement is still reliable despite the short measurement time used.

Influence of measurement condition

Further tests have been performed while changing systematically one factor and keeping the other factors of the measurement condition constant. The mean intra-individual confidential interval describes the impact on the measured values of f_s while excluding the differences between the units caused by production variation:

Changed factor	Mean Intra - Individual confidential interval	Signal	Constant Conditions
Voltage (0.1V, 0.25V, ;0.5V, 1V)	**+- 3,01%**	Sine sweep up, multitone	0.5 s 20 – 5000 Hz
Time (0.2s , 0.5s, 1s, 2s)	**+- 0,78%**	Sine sweep up, multitone	0.25 V 20 – 5000 Hz
Sweep Direction (upwards and downwards)	**+- 1,91%**	Sine sweep up, sine sweep down	20 – 5000 Hz, 0.2 s, 0.5 s, 0.1 V, 0.5 V
Resolution Stimulus (6 , 12, 24 and 48 lines/octave)	**+- 0,51%**	multitone	1s ; 0.25 V, 0.5 V
Polarity (regular, inverted)	**+- 0,24%**	sine sweep, multitone	0.5 s ; 0.25 V; 20 – 5000 Hz
Orientation (Cone to top, side, bottom)	**+- 1,13%**	Sine sweep up, multitone	0.5 s ; 0.25 V; 20 – 5000 Hz
Climate a) 30° C, 46% humidity b) 20° C, 57% humidity	**+- 4,05%**	sine sweep, multitone	0.5 s ; 0.25 V ; 20 – 5000 Hz
History (order of tests)	**+- 4,62%**	Sine sweep, multi tone signal	0.5 s ; 0.25 V 20 - 5000 Hz
Measurement Technique (R&D contra QC system)	**+- 0,69%**	Multitone signal	1s, 0.1 V

Conclusion: The voltage, orientation, climate and history are the dominant factors causing variation of the measured resonance frequency f_s which are in the order of magnitude of the production variances.

How to define tolerances for fs ?

General comments	The discussion in this application note and the results of the practical investigation show that the measured resonance frequency depends on the following main factors 1. total mass M_{ms} of the moving parts including glue used for assembling 2. compliance C_{ms} of the suspension parts 3. climate before and during testing 4. test condition (excitation, orientation) 5. instrument (sensor and data post processing) Only the first two factors (Compliance C_{ms} and total mass M_{ms}) have a direct influence on the perceived sound quality when the device under test is used in the final application.
Correspondence with mass M_{ms}	Variation of the total mass M_{ms} causes not only variation of the bandwidth but also the sensitivity in the pass band. Thus defining the tolerances $L_{SPLMEAN}$ for the mean SPL level in the pass band and the allowed limits L_{fs} of the resonance frequency the following correspondence should be considered: $L_{fs} \approx 10^{-L_{SPLMEAN}/20dB} \cdot 50\%$ where $L_{SPLMEAN}$ is a positive tolerance level of the mean SPL in dB and L_{fs} is a relative tolerance (deviation divided by f_s) of the resonance frequency in percent. For example an allowed variation of 0.5 dB in SPL mean would correspond with 4.7% variation of f_s.
Correspondence with compliance C_{ms}	Variation of the compliance C_{ms} causes not only variation of the bandwidth but also variation of the peak displacement below resonance. Defining the tolerances L_x for the peak displacement in percent and the allowed limits L_{fs} of the resonance frequency the following correspondence should be considered: $L_{fs} \approx L_x / 2$ where L_x is a relative tolerance (deviation divided by X_{peak}) of the peak displacement X_{peak} in percent and L_{fs} is a relative tolerance (deviation divided by f_s) of the resonance frequency in percent. For example an allowed variation of 20 % Peak displacement would correspond with 10% variation of f_s.
Correspondence with climate variation	The dependency of the compliance C_{ms} and other loudspeaker parameters (e.g. mechanical resistance R_{ms}) on temperature and humidity is caused by the properties of the material used. New material for spider and surround are required to reduce this variation. However, the climate condition during the end-of-line testing are usually not constant and the tolerances for f_s should be larger than required by other factors. The influence of the ambient temperature can be compensated by performing a recalibration with golden reference units stored under identical conditions. It is recommended to shift narrow limits automatically by using a model which describes the relationship between resonance frequency and temperature
Measurement condition and instrument	This application note shows that by using a modern measurement instrument and by performing the measurement under optimal and identical conditions (orientation of the speaker, stimulus, sufficient signal to noise ratio, sensitive sensors, signal processing) reliable and reproducible results can be generated even in a very short measurement time (500 ms).

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