

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Sound system equipment –
Part 22: Electrical and mechanical measurements on transducers**

**Équipements pour systèmes électroacoustiques –
Partie 22: Mesurages électriques et mécaniques sur transducteurs**



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SOUND SYSTEM EQUIPMENT –

Part 22: Electrical and mechanical measurements on transducers

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The text of this International Standard is based on the following documents:

CDV	Report on voting
100/3311/CDV	100/3424/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60268 series, published under the general title *Sound system equipment*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
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INTRODUCTION

Measurements of the electrical and mechanical state variables have become increasingly important for the following reasons:

- Maximum sound pressure output is limited by voice coil heating and transducer nonlinearities. The large signal behaviour of loudspeakers can be described by nonlinear and thermal models using lumped parameters. These physical characteristics are important for transducer design and system integration.
- Mechanical vibration of the diaphragm determines the radiated sound. The modal vibration of the radiator's surface can be predicted by numerical simulations (FEA) and directly measured by laser vibrometry. This data represents important transducer characteristics that can be used to design the desired directivity into the system's acoustical output.
- DSP plays an important role in active systems. Digital pre-processing of the audio stream requires reliable transducer property information to protect the transducer against thermal and mechanical overload and to actively compensate for linear and nonlinear distortion generated in the output signal.

SOUND SYSTEM EQUIPMENT –

Part 22: Electrical and mechanical measurements on transducers

1 Scope

This part of IEC 60268 applies to transducers converting an electrical input signal into a mechanical or acoustical output signal. However, if the electrical input terminals and the surface of the radiator are accessible, this document can also apply to passive and active sound systems such as loudspeakers, headphones, TV-sets, multi-media devices, personal portable audio devices, automotive sound systems and professional equipment. This document describes only electrical and mechanical measurements that help assess the transfer behaviour of the device under test (DUT). This includes operating the DUT in both the small- and large-signal domains. The influence of the target application's acoustical boundary conditions (e.g. car interior) can also be considered in the physical evaluation of the sound system. Perception and cognitive evaluations of the reproduced sound and the impact of perceived sound quality are outside the scope of this document.

NOTE This document does not apply to microphones and other sensors. Implementation of this document does not require access to the sound pressures generated in the near or far fields of the radiator. Directivity and other characteristics describing the electro-acoustical transfer properties are described in IEC 60268-21, which covers acoustical measurements. The practical application of the measurements for research and development (R&D), end-of-line testing (QC) and evaluation in the final target application (TA) is discussed in Annex A.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60263:1982, *Scales and sizes for plotting frequency characteristics and polar diagrams*

IEC 60268-1:1985, *Sound system equipment – Part 1: General*

IEC 60268-2:1987, *Sound system equipment – Part 2: Explanation of general terms and calculation methods*

IEC 60268-11:1987, *Sound system equipment – Part 11: Application of connectors for the interconnection of sound system components*

IEC 60268-12:1987, *Sound system equipment – Part 12: Application of connectors for broadcast and similar use*
IEC 60268-12:1987/AMD1:1991

IEC 60268-21:2018, *Sound system equipment – Part 21: Acoustical (output-based) measurements*

IEC 62458:2010, *Sound system equipment – Electroacoustical transducers – Measurement of large signal parameters*

IEC 62459:2010, *Sound system equipment – Electroacoustical transducers – Measurement of suspension parts*

ISO 3:1973, *Preferred numbers – Series of preferred numbers*

ISO/IEC GUM:1995, *Guide to the expression of uncertainty in measurement (GUM)*

3 Terms, definitions and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1 Terms and definitions

3.1.1

linear behaviour

behaviour of the DUT at small amplitudes where the relationship between input and output signal can be modelled by a linear system and described by a linear transfer function

3.1.2

reference unit

DUT having measured properties representative of units in the sample lot passing the end-of-line test

3.2 Abbreviated terms

DUT device under test

SPL sound pressure level

FEA finite element analysis

FT Fourier transform

4 Type description

The type description shall be provided by the manufacturer, including the following information:

- transduction principle (e.g. electro-dynamical, capacitive, electro-magnetic transducer);
- system description including operation principle (e.g. the number of the transducers used in the loudspeaker system);
- acoustical loading (e.g. horn loading and enclosure types, such as bass reflex, column, line array, ...);
- power amplification (e.g. maximum output power, class type, minimum load impedance, ...);
- DSP processing (e.g. equalizer, active protection), if any.

5 Marking of terminals and controls

The terminals and controls shall be marked in accordance with IEC 60268-1 and IEC 60268-2.

6 Physical characteristics

6.1 Dimensions

The outer dimensions of the DUT shall be specified.

6.2 Mass

The total mass of the DUT when ready for use shall be specified.

6.3 Connectors and cable assemblies

Cable assemblies and connectors shall be in accordance with IEC 60268-11 and IEC 60268-12.

NOTE In some circumstances, the connectors that are currently standardized are unsuitable and the use of other types is unavoidable.

7 Conditions

7.1 Rated conditions

Standard measuring conditions are defined in 7.3. To obtain the actual conditions for the measurement, some values (known as "rated conditions") shall be taken from the manufacturer's specification.

These rated conditions are not subject to measurement, but they constitute the basis for performing the measurements to determine the other characteristics.

The following rated conditions are of this type and shall be stated by the manufacturer:

- rated maximum input voltage (or the rated maximum sound pressure level);
- rated maximum input power;
- evaluation point of the reference displacement;
- rated frequency range;
- rated impedance;
- rated climate conditions.

7.2 Climatic conditions

7.2.1 Conditions for normal testing

IEC 60268-1 states that tests should be carried out in the following environment in order to prevent the influence of temperature and humidity that can affect the properties of the drive unit suspensions:

- ambient temperature T_{norm} : 15 °C to 35 °C;
- relative humidity: 25 % to 75 %;
- air pressure: 86 kPa to 106 kPa.

7.2.2 Conditions for climatic testing

The manufacturer shall specify the ambient temperature T_A and other climatic conditions under which the DUT is operated during thermal testing in accordance with 25.1.4.

7.3 Standard measuring conditions

The DUT shall be understood to be under standard measuring conditions if all of the following conditions are specified and implemented:

- a) the DUT to be measured is mounted in accordance with Clause 13;
- b) the acoustical environment is specified and selected from those given in Clause 9;

NOTE The environment (e.g. car interior) might influence the acoustical load and the mechanical state of the transducer. If the amplitude of the stimulus used in the measurements is adjusted based on the rated maximum (output) sound pressure level L_{MAX} in accordance with IEC 60268-21, the acoustical environment is considered.

- c) unwanted electrical, mechanical or acoustical signals (e.g. noise) generated by other sources shall be kept at the lowest levels possible because their presence can obscure low-level signals. Data related to signals that are less than 20 dB above the noise level in the frequency band being considered shall be discarded or marked as corrupted by noise;
- d) the DUT is acclimatized to the normal climatic conditions (normal ambient temperature $T_A = T_{\text{norm}}$) in accordance with 7.2.1;
- e) additional cooling periods are required between successive tests if the amplitude compression $C(f) > 0,5$ dB is in accordance with IEC 60268-21;
- f) the DUT is supplied with a test signal with specified properties (spectrum, duration, etc.) in accordance with Clause 8 at a specified RMS input value $\tilde{u}$ for the rated frequency range in accordance with Clause 16;
- g) attenuators, equalizers, dynamics and any other active control elements shall be set to their "normal" position as stated by the manufacturer. If other positions are chosen, for example, those providing a maximally flat frequency response or minimum attenuation, they shall be specified;
- h) measuring equipment suitable for determining the wanted characteristics is connected in accordance with Clause 11.

8 Test signals

8.1 General

Some measurements can be performed by using any audio signal $s(t)$ as an input signal (stimulus) applied to the electro-acoustical device under test (DUT) while other measurement techniques use test signals as specified in IEC 60268-21.

8.2 Small-signal condition

The device under test shall be excited by a stimulus $s(t)$ generating the voltage $u(t) = \alpha \tilde{u}_{\text{max}} s(t)$ at the terminals scaled by the maximum input value $\tilde{u}_{\text{max}}$ and scaling factor α . The rated maximum input value $\tilde{u}_{\text{max}}$ shall be specified by the manufacturer of the DUT in accordance with 16.1. The scaling factor α shall be less than 0,1 to ensure negligible heating of the voice coil in electro-dynamic transducers ($\Delta T_v < 5$ K) and linear behaviour of the device under test. The nonlinear distortion components measured through the excitation of a single tone, two tone or multitone stimulus shall be 40 dB below the fundamental signal components.

9 Acoustical environment

9.1 General

Electrical and mechanical measurements shall be made under one of the conditions in 9.2 to 9.8. The acoustical environment used for testing shall be stated.

9.2 Free-field conditions

An environment, which fulfills free-field conditions in full space in accordance with IEC 60268-21, can be used for electrical and mechanical measurements. If the environment (e.g. anechoic room at low frequencies) does not fulfil these free-field conditions over the entire frequency range of the measurement, the manufacturer shall state the valid frequency range.

9.3 Half-space, free-field conditions

An environment, which fulfills free field condition in a half space in accordance with IEC 60268-21 can be used for electrical and mechanical measurements. These conditions shall be satisfactorily met with a reflecting plane of sufficient size.

If the environment (e.g. half space anechoic room at low frequencies) does not fulfil these half-space free field conditions over the entire frequency range of the measurement, the manufacturer shall state the valid frequency range.

9.4 Free-air condition

Acoustical conditions that approach free-field condition over the frequency range of interest shall be used. Other environments shall be considered satisfactory when the reflected sound components are sufficiently suppressed to ensure an accuracy of $\pm 5\%$ in the measured amplitude and phase values of the electrical input impedance curve at the specified frequency. If the environment (e.g. a small measurement room at low frequencies) does not fulfil these conditions over the entire frequency range of the measurement, the manufacturer shall state the valid frequency range.

NOTE The free-air condition is usually applied to transducers operated without enclosure but firmly clamped by a fixture to measure the electrical and mechanical state of the transducer.

9.5 Target application conditions

Acoustical conditions that correspond with the final target application of the device under test (e.g. sound system mounted in a car, horn compression driver mounted on a horn).

9.6 Vacuum condition

9.6.1 General

Acoustical conditions which approach those of no air.

9.6.2 Method of measurement

Transducer electrical impedance are measured and stored. The transducer is then placed in a vacuum chamber and the evacuation is started. Note if any outgassing from glues or plastic materials occurs – the vacuum will be drawn down slower than expected. Transducer electrical impedance is then measured and stored. The vacuum is then released to restore normal atmospheric pressure. The transducer electrical impedance is measured and stored, and the data is then compared to the initial stored measurement to see if any changes have occurred due to material(s) changes from outgassing.

9.7 Plane-wave tube condition

A plane-wave tube is intended to provide an approximately constant acoustical impedance with a value $\rho_0 c$ identical to the specific impedance of air.

NOTE Plane-wave tubes are used to provide a standard load for the testing of compression drivers, see AES-11d-2012 [1]¹.

9.8 Non-acoustical measurement condition

Electrical and mechanical measurements can be performed in a room of sufficient size (typically $> 8 \text{ m}^3$). The size of the room depends on the space required around the DUT to avoid any additional acoustical loading of the DUT and to ensure stable climate conditions during the test.

¹ Numbers in square brackets refer to the Bibliography.

10 Positioning of the radiator

10.1 Rated geometrical conditions

10.1.1 General

The position and orientation of the diaphragm, cone or other kind of radiator used in the DUT shall be stated using the radiator's reference point $\mathbf{r}_{r,ref}$, the normal vector $\mathbf{n}_r$ and the orientation vector $\mathbf{o}_r$ as illustrated in Figure 1.

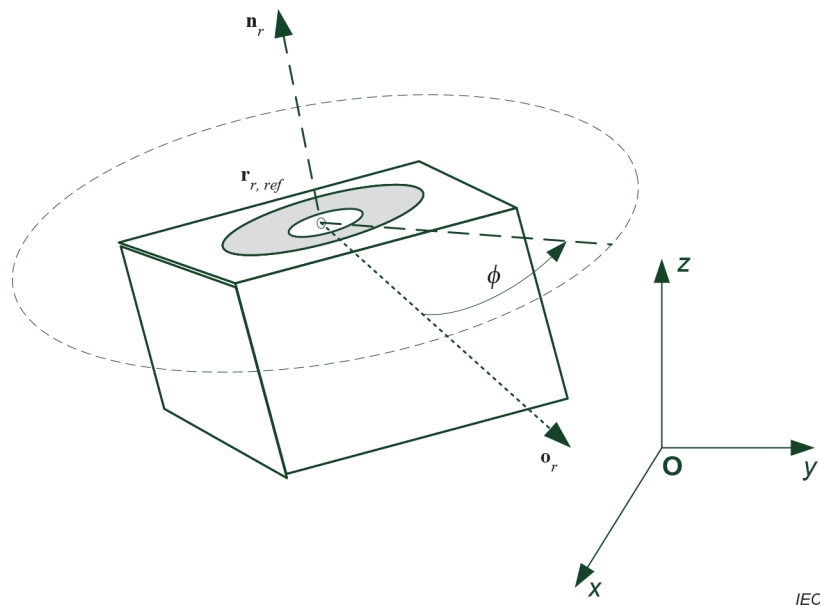


Figure 1 – Rated conditions used to describe the geometry and position of the radiator in the coordinate system

10.1.2 Reference plane and normal vector

The reference plane with the normal vector $\mathbf{n}_r$ shall be used to define the reference axis and the reference point $\mathbf{r}_{r,ref}$.

NOTE For symmetrical structures, the reference plane is usually parallel to the radiating surface at the rest position of the radiator. For asymmetrical structures, the reference plane is better indicated by means of a diagram.

10.1.3 Reference point

The reference point $\mathbf{r}_{r,ref}$ shall be a point on the radiator's surface intersecting the reference plane. The position of the reference point $\mathbf{r}_{r,ref}$ shall be specified by the manufacturer.

NOTE For symmetrical structures, reference point $\mathbf{r}_{r,ref}$ is usually the point of axial symmetry of the radiator within the reference plane. For asymmetrical structures, the reference point is better indicated by means of a diagram.

10.1.4 Orientation vector

The orientation vector $\mathbf{o}_r$ defines the orientation of the radiator within the reference plane and the direction of the azimuthal angle ϕ in spherical coordinates.

NOTE The preferred orientation vector places the reference point $\mathbf{r}_r$ at the origin O of the coordinate system, pointing the normal vector $\mathbf{n}_r$ of the reference plane into the z -direction while the polar angle $\theta = \theta$ turns the audio system in such a way that the orientation vector $\mathbf{o}_r$ (e.g. top of the enclosure) points into the x -direction.

10.2 Target application condition

The position and orientation of the radiator with respect to the target environment (car interior, pinna adaptor with ear canal simulator, etc.) shall be described by means of a diagram appended to the measurement results.

11 Measurement equipment and test results

Graphical results shall conform to the preferred aspect ratios in IEC 60263.

Frequency data, if provided in addition to the graphs, shall be at the ISO R40 preferred frequencies, unless otherwise stated.

The measurement of the voltage at the terminals of the device under test shall be made using sensing wires in addition to the two driving wires (four wire technique) so that negligible current is generated in the sensing wire.

NOTE The resistance of the cables and current sensors (e.g. measurement resistor) can affect the accuracy of the impedance measurement and the input voltage at the device under test.

12 Accuracy of the mechanical and electrical measurement

Probable error sources in both the instrumentation and measuring environment shall be identified, quantified and their contribution shall be specified. Uncertainties in the position and calibration of the sensors shall be stated. This information shall be included with the test report.

13 Mounting of the DUT

13.1 Mounting and acoustic loading of drive units

The performance of the drive unit (transducer) is determined by the properties of the unit itself and its acoustic loading. The acoustic loading depends upon the mounting arrangement, which shall be clearly described in the presentation of the results.

One of the following types of mounting shall be used:

- a) half-space free-field condition generated by mounting the transducer flush with a plane reflecting surface according conditions defined in 9.3. Half-space loading for transducers is preferred;
- b) a standard baffle with a plane front surface that is acoustically reflecting, as specified in IEC 60268-21;
- c) a standard measuring enclosure (type A or type B) as specified in IEC 60268-21, generating a defined rear air volume and radiation condition at the front of the transducer;
- d) a loudspeaker driver comparison chamber as specified in AES X223 [2];
- e) a test cabinet generating a defined air load and radiation condition at the front of the transducer for end-of-line testing and relative measurements;

NOTE An additional chamber located at the rear side of the transducer can be used to provide additional noise isolation or it could be used to consider the influence of the air volume of a sealed box in the target application.

- f) a defined horn, coupler or other kind of wave guide that couples the radiating surface of the transducer in the target application to the surrounding sound field;
- g) a plane wave tube as specified in 9.7;
- h) the transducer is operated in free air and is firmly clamped by a fixture to reduce the vibration of the frame and magnet;

- i) the transducer is operated in vacuum and is firmly clamped by a fixture to measure the properties of the transducer without air load. The lumped parameters of the transducer measured under this condition use letter "s" instead of the "d" as a suffix.

13.2 Mounting and acoustic loading of an electro-acoustic system

Electro-acoustic systems are usually measured without an additional baffle. If the manufacturer specifies a special type of mounting for the loudspeaker system, this shall be used for the measurement. The mounting method used shall be specified with the results.

13.3 Requirements for laser vibrometry

The measurement of the mechanical vibration on the target surface (radiator, enclosure, etc.) requires a fixed clamping of the device under test relative to the sensor. The vibration at the clamping point shall be at least 20 dB below the vibration on the target surface. It is recommended to operate the radiator in the vertical position where the normal vector $\mathbf{n}_r$ is perpendicular to the gravity. This will avoid any bias in the resting position of the radiator.

14 Preconditioning

Temporary or permanent changes may take place when a signal generating high displacement is applied to the new DUT for the first time. Sufficient preconditioning shall be performed according to the intended use of DUT in the field (e.g. application bandwidth and enclosure type).

NOTE For example, the suspension of a driver is subject to significant changes in its mechanical properties. The DUT also suffers from the effects of voice coil heating and cooling in electro-dynamic transducers.

The DUT shall be preconditioned before measurements are performed by applying a broadband signal at half the maximum input value $\tilde{u}_{\max}$ in accordance with IEC 60268-21 for at least one hour (3h recommended for woofers).

Before proceeding with the measurement, the period of preconditioning shall be followed by a recovery period of at least one hour to ensure that the temperatures of the internal parts are re-acclimatized to the ambient conditions defined in 7.3.

15 Rated ambient conditions

15.1 Temperature ranges

15.1.1 Performance limited temperature range

The temperature range over which the variation of the characteristics of the DUT shall not exceed the specified tolerances.

15.1.2 Damage limited temperature range

The temperature range that, if exceeded during previous product life, may result in permanent changes in the operating characteristics of the DUT. These temperature thresholds shall be specified separately for operation and storage.

15.2 Humidity ranges

15.2.1 Relative humidity range

The relative humidity range over which the variation of the characteristics of the DUT shall not exceed the specified tolerances.

15.2.2 Damage limited humidity range

The relative humidity range that, if exceeded during operation or storage, may result in permanent changes in the operating characteristics of the DUT.

16 Electrical signals at transducer terminals

16.1 Rated maximum input value

16.1.1 Conditions to be specified

The manufacturer specifies the rated maximum input value $\tilde{u}_{\max}$ defined as the RMS value

$$\tilde{u}_{\max} = \left(\frac{1}{T_s} \int_0^{T_s} u^2(t) dt \right)^{1/2}$$

of the measured voltage signal $u(t)$ at the transducer terminals under standard measuring conditions, in accordance with 7.3, using a specified broadband stimulus limited by the frequencies f_l and f_u of the rated frequency band within the excitation time $T_s = 1$ s.

The properties of the broadband stimulus $s(t)$, such as the spectral properties, the crest factor and the lower and upper limits of the rated frequency band, shall be stated by the manufacturer.

NOTE The rated maximum input value $\tilde{u}_{\max}$ can be determined either by a direct measurement or indirectly derived from the rated maximum sound pressure value $\tilde{p}_{\max}(r_e)$ as specified in IEC 60268-21.

16.1.2 Direct measurement

16.1.2.1 Test equipment

The following equipment or equivalent shall be included in the chain of measurement:

- a pink noise generator and/or multi-tone generator in accordance with IEC 60268-21;

NOTE 1 A DUT intended for full-band audio signals can be tested using a broadband stimulus such as a multi-tone complex with sufficient resolution (at least ten lines per octave), a pink noise signal or any noise like signal such as the simulated programme signal in accordance with IEC 60268-21. For a DUT with a small usable bandwidth in the target application (e.g. subwoofer), a sufficiently good approximation of the "broadband" signal can be a sinusoidal signal, a Hann burst signal or a narrow band noise in accordance with Clause 8.

- a weighting network to obtain the noise signal in accordance with IEC 60268-21;
- a clipping network to implement a specified crest factor;
- an optional power amplifier for passive electro-acoustical DUT.

The amplitude of the frequency response between the input of the optional power amplifier and the voltage at the input terminals of a passive DUT shall be constant to within $\pm 0,5$ dB in the frequency range from 20 Hz to 20 kHz. The clipped noise at the terminals of the loudspeaker under test shall have a frequency distribution as specified in IEC 60268-21 and a peak-to-RMS ratio of between 1,8 and 2,2. The optional power amplifier shall have an output impedance not greater than 1/3 of the rated impedance of the passive DUT. The amplifier shall be capable of supplying the passive DUT without limiting the peak sinusoidal voltage. The peak voltage shall be at least twice the voltage of the test noise.

16.1.2.2 Test procedure

- a) The manufacturer shall define a test value $\tilde{u}_{\text{test}}$ of the broadband stimulus in the rated frequency band that is used for further testing. This value considers the intended application and behaviour of the DUT (e.g. permissible heating and maximum mechanical excursion) so that damage to the DUT during the following test can be avoided.

NOTE 2 The permissible heating can be checked by measuring the increase of voice coil temperature in accordance with 24.2. The maximum mechanical excursion can be measured in accordance with 23.5.

- b) The DUT shall be placed in a room as specified in 9.8 with climate conditions as specified in 7.2.
- c) The DUT shall be tested under a specified climatic condition for a continuous period of 100 h at the test value $\tilde{u}_{\text{test}}$ of the input stimulus.

NOTE 3 Since the test value $\tilde{u}_{\text{test}}$ is constant during the 100 h test, the heating of the DUT will cause thermal compression of the acoustical output and the sound pressure level will fall below the rated maximum sound pressure $\tilde{p}_{\text{max}}(r_e)$.

- d) Immediately after the test, the DUT shall be stored under climate conditions that would normally exist in ordinary rooms or laboratories. Unless otherwise specified, the recovery period shall be 24 h.
- e) At the end of the recovery period, the electrical, mechanical and acoustical characteristics of the DUT are measured. If the measured values are within the tolerances of the values stated in the data sheet, the DUT may be considered to have fulfilled the requirement of this test and the test value $\tilde{u}_{\text{test}}$ is assigned to the rated maximum input voltage $\tilde{u}_{\text{max}}$. The permissible shift of the resonant frequency shall be defined in the data sheet.

If the DUT has been damaged during this test or the measured characteristics are outside the defined tolerances, the test shall be repeated using a new DUT at a reduced test value $\tilde{u}_{\text{test}}$ until the rated maximum input value $\tilde{u}_{\text{max}}$ is determined.

17 Electrical input power

17.1 Real input power

The real input power is the product of instantaneous voltage $u(t)$ and current $i(t)$

$$P_{\text{REAL}}(t) = \frac{1}{T} \int u(t+\tau) i(t+\tau) d\tau$$

averaged over a time T . The integrator shall be implemented by a low-pass filter having a cut-off frequency of 1 Hz.

NOTE The power $P_{\text{REAL}}(t)$ according IEC 60050-151 considers all losses in the transducer represented by the real part of the electrical input impedance including nonlinear and time varying properties. This characteristic is required to model the thermal dynamics of the transducer and the heat transfer to the environment.

17.2 Power dissipated in DC resistance

The input power dissipated in $P_{\text{Re}}(t) = \tilde{i}^2(t) R_{\text{E}}(t)$ is product of squared RMS value of the input current $i(t)$ and the instantaneous DC resistance $R_{\text{E}}(t)$.

NOTE This power $P_{\text{Re}}(t)$ is a useful characteristic for modelling the heating of the voice coil. The power dissipated in $R_{\text{E}}(t)$ does not consider the heating of the pole plates by eddy current and any mechanical or acoustical losses.

17.3 Power dissipated in rated impedance

The power dissipated in the rated impedance $P_{E,N}(t) = \tilde{u}^2(t) / Z_N$ is calculated by dividing the squared RMS voltage at the input terminals by the rated impedance Z_N in accordance with 18.2.

NOTE This characteristic $P_{E,N}$ is a rough approximation of real input power that neglects the frequency dependency of the input impedance and any nonlinear and time varying properties. This characteristic is required to describe the available electric input power provided by an amplifier with low output impedance (voltage source).

17.4 Rated maximum input power

The rated maximum noise power $P_{\max} = \tilde{u}_{\max}^2(t) / Z_N$ is calculated by dividing the squared value of the rated maximum input voltage $\tilde{u}_{\max}$ by the rated impedance Z_N in accordance with 18.2.

NOTE This characteristic $P_{\max}$ is a rough approximation of real input power that neglects the frequency dependency of the input impedance and any nonlinear and time variant properties.

18 Electrical input impedance

18.1 Complex electrical impedance

18.1.1 General

The electrical input impedance is the linear transfer function $Z_E(f) = U(f) / I(f)$ between the input current $i(t)$ and terminal voltage $u(t)$. The electrical impedance in accordance with IEC 60050-151 shall be measured under small signal conditions in accordance with 8.2.

NOTE The impedance measured with a high-amplitude stimulus can be affected by the nonlinear, visco-elastic and thermal properties of the DUT as discussed in Klippel [3].

The electrical input impedance shall be measured in the small signal domain by using an attenuated stimulus (scaling factor $\alpha \leq 0,1$) or by performing measurements at reduced levels until the observed response is unchanged, verifying linear conditions.

18.1.2 Method of measurements

The transducer is excited by a broadband stimulus $s(t)$ generating the voltage $u(t) = \alpha \tilde{u}_{\max} s(t)$ at the terminals scaled by the maximum input value $\tilde{u}_{\max}$ and a scaling factor α to ensure small signal conditions in accordance with 8.2. To measure at sufficient spectral resolution and SNR in the small-signal domain, it is recommended to use a sparse multi-tone complex stimulus in accordance with IEC 60268-21. This signal shall have at least 8 tones per octave for frequencies $f < f_s/2$ and $f > 2f_s$, and at least 24 tones per octave in the frequency band $f_s/2 < f < 2f_s$. The properties of the stimulus $s(t)$, the measurement time T_s and either the RMS-value $\tilde{u} = \alpha \tilde{u}_{\max}$ or the scaling factor α shall be stated by the manufacturer.

- The complex amplitudes of the spectral components $U(f) = F\{u(t)\}$ are determined by using a time-frequency transformation such as the Fourier transform $F\{\}$.
- The input current $i(t)$ is measured and the complex amplitudes of the spectral component $I(f) = F\{i(t)\}$ are calculated. If the total nonlinear distortion found in the measured current signal at the resonance frequency f_s is larger than 3 %, the measurement shall be repeated with reduced scaling factor α .

NOTE Time windowing is unnecessary if the length of the multi-tone stimulus corresponds with the length of the FT. The resulting fundamental components appear at the excitation frequencies while spectral components located on the other frequencies reveal nonlinear distortion and noise.

c) The complex impedance is calculated by

$$\underline{Z}_E(f_{\text{fund}}) = \frac{\underline{U}(f_{\text{fund}})}{\underline{I}(f_{\text{fund}})}$$

providing the magnitude response $|\underline{Z}_E(f_{\text{fund}})|$ and the phase response $\varphi_E(f_{\text{fund}}) = \arg(\underline{Z}_E(f_{\text{fund}}))$ at the fundamental frequencies f_{fund} excited by the stimulus.

To avoid a flattening of the resonance peak which affects the accuracy of the small signal parameters (mechanical quality factors), smoothing shall not be applied to the measured impedance curve.

18.2 Rated Impedance: characteristic to be specified

The rated impedance Z_n is the value of a pure resistance to be substituted for the loudspeaker's complex input impedance $\underline{Z}_E(f)$. The lowest value of the modulus of the impedance $|\underline{Z}_E(f)|$ in accordance with 18.1 in the rated frequency range shall not be less than 80 % of the rated impedance Z_n . The rated impedance Z_n shall be stated by the manufacturer when defining the available electric power of the source.

19 Vibration of the radiator surface

19.1 General

Measurement of the vibration of the radiator's surface provides a deeper insight into the mechanical system and the radiated sound. A non-contacting sensor (e.g. laser vibrometer) shall be used to measure the motional state variable (displacement, velocity or acceleration) in the direction of the normal vector $\mathbf{n}_r$. This ensures that there is no undesirable mass loading affecting the DUT.

A proximity sensor that yields the instantaneous position of the measurement point is recommended to reveal the geometry of the surface and the displacement from the rest position.

This is important for reliably detecting the positive and negative peak displacement and the DC displacement dynamically generated by the transducer's nonlinearities. Velocity and acceleration can be calculated by differentiation of the time signals. Sensors measuring velocity or acceleration directly generally provide better SNR at higher frequencies. Care shall be taken to ensure that the displacement signal calculated by integration does not contain significant errors due to noise or optical problems in the detected velocity or acceleration signal.

19.2 Displacement of a surface point $\mathbf{r}_r$

19.2.1 General

The displacement $x(t, \mathbf{r}_r)$ at surface point $\mathbf{r}_r$ on the radiator's surface is measured in the direction of the normal vector $\mathbf{n}_r$ while applying a specified stimulus $s(t)$ to the input of the DUT. The position of the surface point is described by coordinates having their origin at the reference surface point $\mathbf{r}_{r,\text{ref}}$. The orientation vector $\mathbf{o}_r$ points into the direction of the x axes for Cartesian coordinates and corresponds to a 0° angle using polar coordinates.

19.2.2 Method of measurements

- a) The DUT is placed under standard measuring conditions in 7.3 while considering the requirements of the laser vibrometry, in accordance with 13.3.
- b) The vibrometer's sensor is focused on the measurement point r_r located on the radiator's surface. Proper clamping of the DUT and positioning of the vibrometer ensures that the sensor is always working at the optimal operating point and there are no unwanted relative movements between the DUT (frame, enclosure,...) and the sensor. It can be necessary to treat the surface area of the radiator to be measured with a diffuse reflecting material. For a single point measurement, white correction ink is recommended. In the case of a complete scan of the radiator's surface, a spray penetrant of suspended inert white powder in a quick-drying solvent is recommended (e.g. Ardox 9D1B). To avoid affecting the mechanical vibrations of the radiator, the application of the reflecting material should be minimal.

If the entire surface of the radiator has been treated, compare the fundamental resonance frequency f_s of the DUT derived from the electrical impedance $Z_E(f)$ measured before and after the treatment. If the change of the resonance frequency exceeds 1 %, the additional mass of the treatment shall be subtracted from the measured mass.

- c) Prior to the measurement, the displacement signal is nulled by subtracting the measured value at the rest position of the radiator's surface when no signal is applied to the DUT's input from the sensor output.
- d) The sensor output signal shall be investigated for errors (e.g. spikes) caused by optical scanning problems at the surface of the radiator. Corrupt data shall not be used for further analysis or for the calculation of characteristics.

NOTE Optical scanning errors can be detected reliably by using a triangulation laser. Two measurements are performed at the same point r_r . The first measurement is performed normally while the second measurement is performed after the distance of the laser is slightly changed along the normal vector n_r . The small change in the measurement distance between the triangulation laser and the measurement point r_r changes the observation angle of the sensor without affecting the position of the laser point on the surface. The optical scanning errors become evident in the correlation between the two measurements.

19.3 Reference displacement

19.3.1 General

The reference displacement $x(t)$ is a state variable of the lumped parameter model. The derivative of the reference displacement (velocity) multiplied with an electro-mechanical transduction factor T_{BI} corresponds to a back EMF that can also be determined by an electrical measurement.

NOTE In electro-dynamical transducers the reference displacement $x(t)$ corresponds to the mean voice coil displacement and the transduction factor (also called force factor) can be expressed by the Bl -product mean induction B seen by the wire length l (see Beranek [4]).

In woofers and midrange transducers, the displacement of the central area of the radiator is close to the reference displacement. In general, multiple measurements on the radiator's surface are carried out to calculate the reference displacement.

19.3.2 Methods of measurement

Depending on the properties of the radiator and the suspension system of the transducer, the reference displacement can be determined by different techniques:

- a) The reference displacement $x(t) = x(t, r_{r,ref})$ shall be measured at the reference point $r_{r,ref}$ if all of the following conditions are fulfilled:
 - the radiator has an axially symmetric geometry and the reference point $r_{r,ref}$ is in the centre of the radiator's surface;
 - the central area of the radiator (enclosed by the voice coil in electro-dynamic transducers) stays sufficiently rigid at the frequencies investigated;

- the relative level L_{rock} of rocking modes, as defined in 20.7.3, is less than -15dB ;

NOTE 1 For woofers, midrange drivers and other axial symmetrical transducers using a rigid cone, surround and spider in their mechanical suspension, the displacement of the voice coil is similar to the displacement of the radiator's central point at low frequencies. However, micro-speakers, tweeters, compression drivers, headphone drivers and other transducers generate modes on the radiator's surface (e.g. rocking modes defined in 20.7.3) that prevent the central point from representing the mean vibration of the voice coil. The deviations in the measured displacement at the central point for these devices can affect the accuracy of the calculated mechanical parameters.

- If one or more of the conditions in a) above are not met, the reference displacement $x(t)$ shall be determined by averaging the displacements measured at a minimum of 4 points $\mathbf{r}_r$ equally spaced from the pivot point (crossing point of the nodal lines of the two rocking modes), where $x(t) = \overline{x(t, \mathbf{r}_r)}$.
- If the position of the pivot point is not known and transducer (e.g. micro-speaker) generates a relative rocking level $L_{\text{rock}} > -3\text{dB}$, the reference displacement shall be calculated as the transversal mode ($n = 0$) in a modal analysis as defined in 20.7.2 based on a minimum of 4 measurement points $\mathbf{r}_r$.
- As an alternative, if the electro-mechanical free model lumped parameters are known for the particular DUT, the reference displacement shall be calculated based on the electrical input signal $u(t)$. In order to describe the reference displacement in the large-signal domain, the model shall consider the dominant nonlinearities in accordance with Clause 23 and the thermal properties in accordance with Clause 24.

NOTE 2 A linear model based on the small-signal lumped parameters cannot describe nonlinear distortions at higher amplitudes, such as the compression of the fundamental component or generation of a DC component.

19.4 Peak and bottom displacement

19.4.1 General

The peak and bottom values of the reference displacement $x(t)$ or the measured displacement $x(t, \mathbf{r}_r)$ of any point $\mathbf{r}_r$ on the target surface are the maximum and minimum values of the time signal $x(t)$ for a defined stimulus. The properties of the stimulus, such as the frequency f of the sinusoidal signal, and the length T of the measurement interval shall be specified.

19.4.2 Method of measurements

- The displacement is measured in accordance with 19.2.
The minimum and maximum value of the signal is determined within a measurement interval of defined length T and the measured value is assigned to time t at the end of the interval.
- The stimulus properties determine how the peak and bottom values are plotted: plotted versus time t for ordinary audio signals (e.g. music); plotted versus frequency f or voltage u for deterministic test signals (for example sinusoidal).

19.5 DC displacement

19.5.1 General

The DC displacement is a low-frequency component (far below the audio band) in the reference displacement $x(t)$ or measured displacement $x(t, \mathbf{r}_r)$ of any point $\mathbf{r}_r$ on the target surface that is generated dynamically by the transducer's nonlinearities.

NOTE The DC displacement is generated by rectification of the AC displacement signal and can be interpreted as a difference-tone intermodulation distortion component (see Klippel [3]). Contrary to harmonic and summed tone intermodulation distortions, which are generated at high frequencies, where the displacement is negligible, the DC component can be the same order of magnitude as the AC displacement.

19.5.2 Method of measurements

- The displacement $x(t)$ is measured in accordance with 19.2.
- The DC displacement $x_{DC}(t) = \overline{x(t)}$ is calculated as the mean value of the displacement within a measurement interval with defined length T and the mean value is assigned to the time t at the end of the interval. Under steady-state input conditions (e.g. single tone), the length T of the measurement interval shall be identical to the length of the stimulus. For measurements with transient stimuli (for example an ordinary audio signal), the length T shall be specified.
- The DC displacement $X_{DC}(f)$ shall be plotted versus instantaneous excitation frequency f if the stimulus is a steady-state tone or a chirp signal with defined frequency-time mapping.

19.6 Displacement transfer function

19.6.1 General

The transfer function $\underline{H}_{X,U}(f_{\text{fund}}, \mathbf{r}_r)$ between terminal voltage $u(t)$ and displacement $x(t, \mathbf{r}_r)$ at a point $\mathbf{r}_r$ on the radiator's surface is measured at logarithmically spaced frequencies f_{fund} with a specified resolution at small amplitudes. ISO R40 frequencies defined in ISO 3 are generally preferred.

NOTE This method can also be applied to the transfer function between the terminal voltage $u(t)$ and the reference displacement $x(t)$.

19.6.2 Method of measurements

- The transducer is excited by a broadband stimulus $s(t)$ generating the voltage $u(t)$ at the terminals. The properties of the stimulus $s(t)$, the measurement time T_s and either the RMS-value $\tilde{u} = \alpha \tilde{u}_{\text{max}}$ or the scaling factor α and maximum input value $\tilde{u}_{\text{max}}$ shall be stated. The complex amplitudes of the spectral components $\underline{U}(f)$ at frequencies f at a specified resolution are determined by using a discrete Fourier transform (DFT), or similar, where $\underline{U}(f) = F\{u(t)\}$.
- The displacement $x(t, \mathbf{r}_r)$ is measured at surface point $\mathbf{r}_r$ in accordance with 19.2 and the complex amplitudes of the spectral component $\underline{X}(f) = F\{x(t, \mathbf{r}_r)\}$ are calculated.
- The complex transfer function shall be calculated as $\underline{H}_{X,U}(f, \mathbf{r}_r) = \underline{X}(f, \mathbf{r}_r) / \underline{U}(f)$ and shall be presented as the magnitude response $|\underline{H}_{X,U}(f, \mathbf{r}_r)|$ and the phase response $\varphi_{X,U}(f, \mathbf{r}_r) = \arg(\underline{H}_{X,U}(f, \mathbf{r}_r))$ at the frequencies f excited by the stimulus.

19.7 Accumulated acceleration level

19.7.1 General

The accumulated acceleration level $L_{AA}(f, \mathbf{r}_a)$ describes the total mechanical vibration on the surface of the radiator (in dB) as a function of frequency f

$$L_{AA}(f, \mathbf{r}_a) = 20 \lg_{10} \left(\int_{S_r} \frac{(s \pi f)^2 |\underline{X}(f, \mathbf{r}_r)|}{a_{\text{ref}}(\mathbf{r}_a)} dS_r \right)$$

using a reference value $a_{\text{ref}}(\mathbf{r}_a)$ depending on the location of a specified observation point $\mathbf{r}_a$ in the sound field defined as

$$a_{\text{ref}}(\mathbf{r}_a) = \frac{\pi \sqrt{2} p_0 |\mathbf{r}_a - \mathbf{r}_r|}{\rho_0}$$

with the reference sound pressure p_0 and the density of air ρ_0 (see Klippel, Schlecht, [5], [6]).

NOTE The reference value $a_{\text{ref}}(\mathbf{r}_a)$ ensures that the accumulated acceleration level $L_{\text{AA}}(f, \mathbf{r}_a)$ can be interpreted as the total potential sound pressure available at the observation point $\mathbf{r}_a$ located in the generated sound field, if the destructive effects of acoustical cancellation are neglected. At low frequencies below the first break-up frequency, where all points on the radiator's surface vibrate in phase and the size of the radiator is small compared to the wavelength λ , the accumulated acceleration level $L_{\text{AA}}(f, \mathbf{r}_a)$ is equal to the sound pressure level $L_p(f, \mathbf{r}_a)$ predicted by the Rayleigh integral.

19.7.2 Method of measurements

- The transfer function $\underline{H}_{X,U}(f, \mathbf{r}_r[m])$ with $0 \leq m \leq M$ shall be measured on the radiator's surface with sufficient spatial resolution ($M > 100$ scanning points) in accordance with 19.6.
- The displacement $\underline{X}(f, \mathbf{r}_r[m]) = \underline{H}_{X,U}(f, \mathbf{r}_r[m])\underline{U}(f)$ shall be calculated for a defined amplitude of the terminal voltage U .
- The accumulated acceleration level at the specified observation point $\mathbf{r}_a$ shall be calculated by

$$L_{\text{AA}}(f, \mathbf{r}_a) = 20 \lg_{10} \left(\sum_{m=1}^M \frac{(2\pi f)^2 |\underline{X}(f, \mathbf{r}_r[m])|}{a_{\text{ref}}(\mathbf{r}_a)} \Delta S_r(\mathbf{r}_r[m]) \right)$$

with the area $\Delta S_r(\mathbf{r}_r[m])$ on the radiator's surface represented by the scanning point $\mathbf{r}_r[m]$.

20 Small-signal lumped parameters

20.1 General

Linear modelling can be applied to the DUT at small amplitudes where the nonlinear properties of the DUT are negligible as defined in 8.2. The measurement of nonlinear distortion in the electrical signals (for example current) at the terminals shall be used to validate the assumptions made in linear modelling.

NOTE Besides the generation of nonlinear distortion, time-varying visco-elastic properties of the suspension can also affect the measurement results of the small parameters.

It is recommended to specify or report the peak displacement generated by the stimulus during the test.

At low frequencies, where the radiator behaves in fundamental (piston) mode, the transfer and vibration behaviour of the transducer and the influence of the mechanical and acoustical load (for example, an enclosure) can be described by a lumped parameter model (see Small [7]). A model with distributed parameters is required to describe the mechanical and acoustical system at higher frequencies.

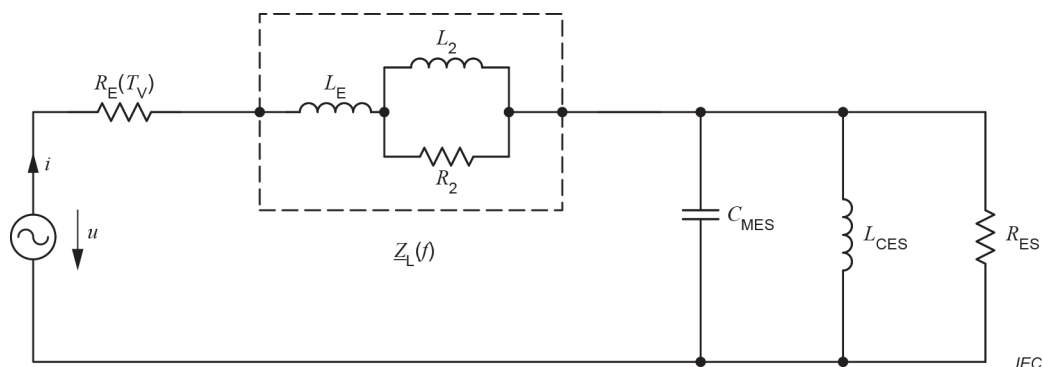


Figure 2 – Equivalent electrical network representing the electrical input impedance using the LR2 model for the lossy inductance of an electro-dynamical transducer

20.2 Electrical parameters

20.2.1 General

The electrical input impedance measured at low amplitudes can be modelled by an equivalent electrical network as shown in Figure 2, which is time-invariant and linear. For the device under test (DUT), the model's lumped parameters are estimated by minimizing the mean squared error between the measured and modelled electrical impedance (complex curve fitting).

20.2.2 DC resistance

20.2.2.1 General

The DC resistance $R_E(T_v)$ of the transducer usually describes the electrical input impedance at frequencies far below the fundamental resonance frequency where the influence of other electrical and mechanical elements is negligible.

20.2.2.2 Method of measurements

The electrical impedance $Z_E(f)$ is measured at a low frequency $f < f_s/8$ which is at least three octaves below the resonance frequency f_s of the transducer.

NOTE The DC resistance $R_E(T_v)$ depends on the voice coil temperature T_v , which varies with the ambient temperature T_A and the electrical stimulus supplied to the transducer.

If the evaluation of voice coil heating in electro-dynamical transducers or the influence of the ambient temperature is not the target of the measurement, the DC resistance R_E of the transducer should be measured under small-signal conditions in accordance with 8.2 and the transducer should be acclimatized to the normal ambient conditions in accordance with 7.3.

20.2.3 Lossy inductance

20.2.3.1 General

The electrical impedance $Z_L(f)$ of the lossy voice coil inductance in electro-dynamical transducers contributes to the electrical impedance $Z_E(f)$ at higher frequencies. The electrical impedance $Z_L(f)$ is represented by an additional electrical network in the model (as shown in Figure 2) or by an analytical description.

20.2.3.2 Method of measurements

- The DC resistance R_E is measured in accordance with 20.2.2 and the electrical impedance $Z_E(f)$ is measured while the movement of the voice coil is blocked.
- The electrical impedance $Z_L(f)$ of the lossy voice coil inductance is the remnant of the electrical impedance $Z_E(f)$ after removing the DC resistance R_E . The modulus and phase response of the electrical impedance $Z_L(f)$ shall be reported versus frequency.

Alternatively, the electrical impedance $Z_L(f)$ shall be reported as a frequency-dependent inductance $L_{EL}(f) = \frac{1}{2\pi f} \Re\{Z_E(f)\}$ representing the imaginary part of the lossy inductance

and by a frequency-dependent resistance $R_{EL}(f) = \frac{1}{2\pi f} \Im\{Z_E(f)\}$ representing the real part of the lossy inductance.

- c) An electrical network, such as the LR2 model as shown in Figure 2, is used for modelling the complex impedance $\underline{Z}_L(f)$ of the lossy inductance. The network is comprised of a multitude of inductances ($L_1, L_2, \dots$) connected in series where at least one inductance (L_2) is shunted by a resistance (R_2). The structure of the network and the lumped parameters calculated by minimizing the modelling error (curve-fitting technique) shall be specified.
- d) Alternatively, a mathematical model, such as Leach [8] or Thorborg [9], can be used to represent the complex impedance $\underline{Z}_L(f)$ of the lossy inductance. The network structure and the lumped parameters calculated by minimizing the modelling error (curve fitting) shall be specified.

NOTE Blocking of the voice coil movement can be avoided if the electrical network or the mathematical model representing the lossy inductance is accurate at higher frequencies ($f > 4f_s$) where the influence of the electrical impedance $\underline{Z}_{EM}(f)$ representing the mechanical resonator is negligible. The Leach model gives a sufficient fitting of the measured curve by using a minimum number of free parameters. The higher complexity of the Thorborg model gives in some cases a superior fitting but a unique solution of the parameter estimation cannot be ensured.

20.2.4 Electrical representation of the fundamental resonator

20.2.4.1 General

An electrical network comprised of the parallel connection of a capacitor C_{MES} (corresponding to moving mass M_{MS}), inductance L_{CES} (corresponding to mechanical compliance C_{MS}) and resistance R_{ES} (corresponding to mechanical resistance R_{MS}) as shown in Figure 2 is used to describe the fundamental vibration mode of the transducer including the air load.

NOTE These parameters do not represent the influence of additional acoustical or mechanical resonances such as port resonances in a vented enclosure or time-varying visco-elastic properties (creep) at low frequencies.

20.2.4.2 Method of measurements

- a) The electrical input impedance $\underline{Z}_E(f)$ is measured in accordance with Clause 18.
- b) Based on the electrical input impedance $\underline{Z}_E(f)$, the electrical DC resistance R_E and the electrical model representing the lossy inductance are determined in accordance with 20.2.2 and 20.2.3, respectively.
- c) Based on the model of the lossy inductance, the impedance $\underline{Z}_L(f)$ is measured at the frequencies $f_s/4 < f < 4f_s$.
- d) The impedance $\underline{Z}_{EM}(f)$ representing the effect of the mechanical elements in the electrical domain is the remnant of the electrical input impedance $\underline{Z}_E(f)$ after removing the electrical DC resistance R_E and the impedance $\underline{Z}_L(f)$ of the lossy inductance.
- e) The capacitor C_{MES} , inductance L_{CES} and resistance R_{ES} of the 2nd order electrical network representing the impedance $\underline{Z}_{EM}(f)$ are calculated in the frequency range $f_s/4 < f < 4f_s$ by minimizing the mean squared error in the estimated amplitude and phase response.

NOTE Some transducers, such as micro-speakers, show significant visco-elasticity at lower frequencies, which increases the compliance and mechanical losses. The impedance $\underline{Z}_{EM}(f)$ of these transducers cannot be described by a 2nd order system and the estimated values for capacitance C_{MES} , inductance L_{CES} and resistance R_{ES} will not be accurate. To avoid this bias, a frequency-dependent compliance, as described in 20.6, can be used in the identification of the mechanical resonator's electrical impedance $\underline{Z}_{EM}(f)$.

20.3 Relative lumped parameters

20.3.1 General

The fundamental vibration mode can be described by relative parameters, such as resonance frequency and quality factors, which can be calculated directly from the equivalent electrical parameters defined in 20.2.4.

NOTE The same relative parameters can also be calculated from the corresponding elements of the mechanical and acoustical equivalent circuit (see Small [7]). However, the identification of the electrical circuit can be accomplished by a single measurement of the electrical signals (voltage, current) at the terminals while the identification of the mechanical and acoustical elements requires a perturbation technique or an additional sensor.

20.3.2 Resonance frequency

Resonance frequency f_s of the fundamental vibration mode found in the transducer operated in free air shall be calculated by

$$f_s = \frac{1}{2\pi} \sqrt{\frac{1}{C_{MES} L_{CES}}} \quad (1)$$

based on the lumped parameter elements identified from the impedance $Z_{EM}(f)$ in accordance with 20.2.4 and the mechanical parameters in 20.4.

NOTE If the visco-elastic behaviour of the mechanical suspension is negligible (creep factor < 10 %) and the impedance $Z_L(f)$ of the lossy voice coil inductance at resonance is small compared to the total electrical impedance $Z_E(f_s)$, the resonance frequency f_s can be determined as the frequency at which the modulus of the electrical impedance has its first principal maximum.

20.3.3 Electrical quality factor

The electrical quality factor Q_{ES} of the fundamental vibration mode found in the transducer operated in free air shall be calculated as

$$Q_{ES} = 2\pi f_s C_{MES} R_E = \frac{R_E}{C_{MS} T_{BI}^2 2\pi f_s} \quad (2)$$

using the equivalent electrical parameters in 20.2.4 and the mechanical parameters in 20.4.

NOTE If the visco-elastic behaviour of the mechanical suspension is negligible (creep factor < 10 %) and the impedance $Z_L(f)$ of the lossy voice coil inductance at resonance is small compared to the total electrical impedance $Z_E(f_s)$, the electrical quality factor Q_{ES} can be calculated according Small [7] as

$$Q_{ES} = \frac{r_0}{r_0 - 1} Q_{TS}$$

where:

r_0 is the ratio of the maximum magnitude of the impedance $Z_E(f_s)$ at the resonance frequency f_s to the DC resistance R_E of the transducer; and

Q_{TS} is the total quality factor as defined in 20.3.5.

20.3.4 Mechanical quality factor

The mechanical quality factor Q_{MS} of the fundamental vibration mode found in the transducer operated in free air shall be calculated as

$$Q_{MS} = 2\pi f_s C_{MES} R_{ES} = \frac{1}{C_{MS} R_{MS} 2\pi f_s} \quad (3)$$

using the equivalent electrical parameters in 20.2.4 and the mechanical parameters in 20.4.

NOTE If the visco-elastic behaviour of the mechanical suspension is negligible (creep factor < 10 %) and the impedance $Z_L(f)$ of the lossy voice coil inductance at resonance is small compared to the total electrical impedance $Z_E(f_s)$, the mechanical quality factor Q_{MS} can be calculated according to Small [7] by

$$Q_{MS} = r_0 Q_{TS}$$

where:

r_0 is the ratio of the maximum magnitude of the impedance $Z_E(f_s)$ at the resonance frequency f_s to the DC resistance R_E of the transducer and

Q_{TS} is the total quality factor as defined in 20.3.5.

20.3.5 Total quality factor

The total quality factor Q_{TS} of the fundamental vibration mode found in the transducer operated in free air shall be calculated as

$$Q_{TS} = \frac{Q_{ES} Q_{MS}}{Q_{ES} + Q_{MS}}$$

using the electrical quality factor in 20.3.3 and the mechanical quality factor in 20.3.4.

NOTE If the visco-elastic behaviour of the mechanical suspension is negligible (creep factor < 10 %) and the impedance $Z_L(f_s)$ of the lossy voice coil inductance at resonance is small compared to the total electrical impedance $Z_E(f_s)$, the total quality factor Q_{TS} can be calculated according to Small [7] by

$$Q_{TS} = \frac{\sqrt{f_1 f_2}}{\sqrt{r_0} (f_2 - f_1)}$$

where:

r_0 is the ratio of the maximum magnitude of the impedance $Z_E(f_s)$ at the resonance frequency f_s to the DC resistance R_E of the transducer.

The frequencies f_1 and f_2 are located with approximate symmetry about $f_s \approx \sqrt{f_1 f_2}$ where $f_1 < f_s < f_2$ and the magnitude of impedance $Z_1 = |Z_E(f_1)|$ and $Z_2 = |Z_E(f_2)|$ are equal having a value $Z_1 = Z_2 = \sqrt{r_0} R_E$.

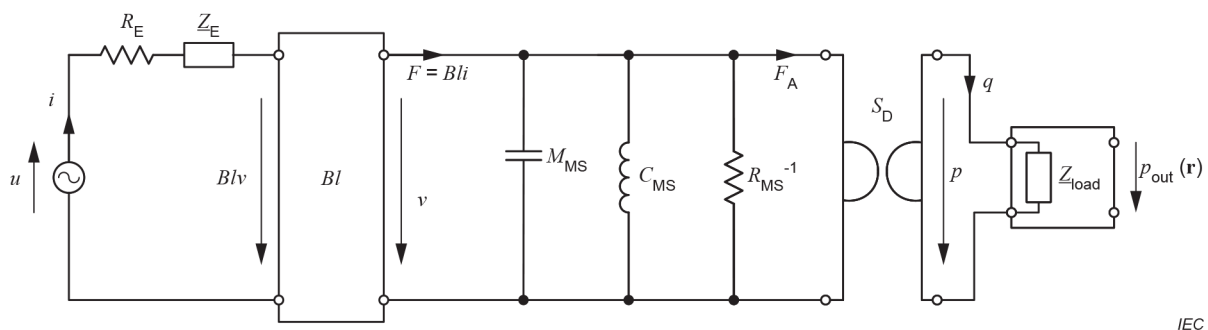


Figure 3 – Analogous lumped parameter network representing the electrical, mechanical and acoustical elements at low frequencies

20.4 Lumped mechanical parameters

20.4.1 General

The fundamental vibration mode of the transducer operated in free air or in half-space shall be described by a lumped parameter model as presented by a network as shown in Figure 3. This network uses a mechanical analogy of the mobility type coupled with a transformer with the electrical domain. The mechanical force F corresponds with current i in Figure 2 scaled by the force factor T_{BI} . A gyrator with the effective radiation area S_D couples the mechanical analogy with the acoustical analogy of the impedance type.

NOTE 1 Other types of mechanical and acoustical analogies can be used in the lumped parameter network as discussed in [4].

The mechanical impedance defined as

$$\underline{Z}_{MS}(f) = \frac{\underline{F}(f, \mathbf{r}_{coil})}{j2\pi f \underline{X}(f, \mathbf{r}_{coil})} = \frac{T_{BI}^2}{\underline{Z}_{EM}(f)} = \frac{1}{j2\pi f C_{MS}(f)} + R_{MS} + j2\pi f M_{MS} \quad (4)$$

is inversely related to the electrical impedance $\underline{Z}_{EM}(f)$ representing the mechanical resonance in the electrical domain scaled by the squared force factor T_{BI}^2 . All the mechanical parameters in Formula (4) consider the influence of the air. The moving mass M_{MS} represents the mass of the moving parts and the air load on both sides of the radiator. Besides the mechanical losses associated with the suspension and the radiation impedance, the resistance R_{MS} considers the losses generated by the turbulent air flows in the gap and in the vent hole of the pole piece. The compliance $C_{MS}(f)$, which is the inverse of the stiffness $K_{MS}(f)$, represents the restoring capability (spring stiffness) of the suspension and the stiffness of air in cavities behind the radiating diaphragm. At low frequencies, the compliance $C_{MS}(f)$ also depends on the frequency f due to the visco-elasticity of the material.

NOTE 2 At low frequencies, visco-elasticity is a pure mechanical phenomenon that increases the compliance $C_{MS}(f)$ and the mechanical resistance $R_{MS}(f)$. As a result, in the relationship between restoring force and displacement, the suspension tends to relax and creep. It loses the ability to store potential energy and converts the supplied energy into heat. This phenomenon is not negligible in transducers such as micro-speakers. It affects the fitting error of the electrical impedance and the accuracy of the measured electrical and mechanical parameters. The increase in compliance $C_{MS}(f)$ increases the AC amplitude of the reference displacement and the DC displacement generated by transducer nonlinearities. The mechanical resistance is approximated in Formula (4) by a constant value $R_{MS} = R_{MS}(f_s)$. The approximation is possible because the frequency dependency of the mechanical resistance $R_{MS}(f)$ has little impact on the transfer behaviour of the transducer below and above the resonance frequency f_s .

If the effects of visco-elasticity are small (creep parameter $\kappa < 10\%$), the compliance can be a constant value $C_{MS}(f) = C_{MS} = C_{MS}(f_s)$ and the mechanical impedance in Formula (4) can be calculated at frequencies $f > f_s/2$.

20.4.2 Method of measurements

20.4.2.1 General

Calculation of the mechanical parameters requires the measurement of at least one mechanical parameter. The calculation in this document uses the relative mechanical parameters defined in 20.3. One of the measurement methods in 20.4.2.2, 20.4.2.3 and 20.4.2.4 shall be used to identify the first mechanical parameter.

20.4.2.2 Added-mass method

This technique performs two measurements of the electrical input impedance on the same transducer where one of the measurements uses a known moving mass perturbation, such as adding a known mass M_{ADD} to the radiator. The variation in the relative parameters between measurements is used to calculate the moving mass M_{MS} of the transducer without added mass.

- The electrical impedance of the transducer without perturbation is measured in free air under small-signal conditions in accordance with Clause 18.
- The equivalent electrical parameters f_s and Q_{ES} of the transducer without perturbation shall be calculated in accordance with 20.2.4.
- After applying an additional mass M_{ADD} onto the radiator's surface, the electrical impedance measurement is repeated in free air under the same small-signal conditions in a) in accordance with Clause 18.
- The equivalent electrical parameters $f_{\text{ADD}} = f_s$ and $Q_{\text{ADD}} = Q_{\text{ES}}$ of the transducer with mass perturbation are calculated in accordance with 20.2.4.
- The moving mass M_{MS} of the transducer without perturbation shall be calculated using Formula (5):

$$M_{\text{MS}} = \frac{M_{\text{ADD}}}{\frac{Q_{\text{ADD}}f_s}{Q_{\text{ES}}f_{\text{ADD}}} - 1} \quad (5)$$

NOTE Formula (5) assumes that force factor T_{Bl} is constant in both measurements (R. Small [7]). A simplified version of this formula, where the quality factors Q_{ADD} and Q_{ES} vanish, is based on the assumption that there is no frequency dependency of the compliance $C_{\text{MS}}(f)$ due to visco-elasticity in accordance with 20.6. If this condition is not fulfilled, the mass perturbation method generates significant errors in the calculated mass M_{MS} .

- Based on the calculated mass M_{MS} and the resonance frequency f_s of the transducer without perturbation, the compliance C_{MS} shall be calculated using Formula (1).
- Using Formula (2), the force factor T_{Bl} shall be calculated based on the measured DC resistance $R_{\text{E}}(T_{\text{V}})$ and the quality factor Q_{ES} .
- The resistance R_{MS} shall be calculated based on the measured quality factor Q_{MS} using the relationship in Formula (3).

20.4.2.3 Box perturbation method

This technique performs two measurements of the electrical input impedance of the same transducer where one of the measurements requires adding stiffness to the mechanical suspension using an enclosed volume of air. The variation in the resonance frequency due to the known acoustical perturbation is the basis for calculating the free air compliance C_{MS} and the equivalent air volume V_{AS} of the transducer.

- The electrical impedance of the transducer is measured in free air (without the enclosure) under small-signal conditions in accordance with Clause 18.
- The equivalent electrical parameters f_s and Q_{ES} of the transducer without acoustical perturbation shall be calculated according to 20.2.4.
- After mounting the transducer in a sealed enclosure of volume V_{T} , the electrical impedance measurement is repeated under the same small signal conditions in a) in accordance with Clause 18.

The enclosure should be carefully sealed without absorption material placed inside. Electro-dynamical transducers with an air leakage path around the voice coil due to a phase plug or missing dust cap should not be tested using this method. The displaced volume of the drive unit shall be subtracted from the volume of the empty enclosure to determine the value of V_T .

- d) The equivalent electrical parameters $f_{CT} = f_s$ and $Q_{ECT} = Q_{ES}$ of the transducer with acoustical perturbation shall be calculated in accordance with 20.2.4.
- e) The equivalent air volume V_{AS} representing the mechanical compliance C_{MS} of the transducer without perturbation shall be calculated using the Formula (6):

$$V_{AS} = V_T \left[\frac{f_{CT} Q_{ECT}}{Q_{ES} f_s} - 1 \right] \quad (6)$$

- f) The mechanical compliance C_{MS} shall be calculated using Formula (7):

$$C_{MS} = \frac{V_{AS}}{\rho_0 c^2 S_D^2} \quad (7)$$

using air density ρ_0 , sound velocity in air c and effective radiation area S_D in accordance with 20.8.2.

- g) Based on the calculated mechanical compliance C_{MS} and the resonance frequency f_s of the transducer without acoustical perturbation, the moving mass M_{MS} shall be calculated using Formula (1).
- h) Using Formula (2), the force factor T_{Bl} shall be calculated based on the measured DC resistance $R_E(T_V)$ and the quality factor Q_{ES} .
- i) The resistance R_{MS} shall be calculated based on the measured quality factor Q_{MS} using the relationship in Formula (3).

20.4.2.4 Laser method

This technique determines the force factor T_{Bl} based on the measured electrical input impedance $Z_E(f)$ and the mechanical transfer function $H_{X,U}(f)$ between the terminal voltage at the transducer and the reference displacement.

- a) The electrical impedance $Z_E(f_{fund})$ of the transducer is measured in free air (without enclosure) under small signal conditions in accordance with Clause 18.
- b) The transfer function $H_{X,U}(f)$ between the terminal voltage and the reference displacement $x(t)$ shall be measured in accordance with 19.3 and 19.6.
- c) The relative lumped parameters representing the mechanical resonator shall be calculated in accordance with 20.3.
- d) The modelled displacement transfer function $H'_{X,U}(f)$ shall be calculated using the electrical and relative parameters.

NOTE In transducers, such as micro-speakers showing significant visco-elasticity, the modelling of the displacement transfer function requires a creep model in accordance with 20.6.

- e) The force factor T_{Bl} shall be calculated by minimizing the mean square error between measured function $H_{X,U}(f)$ and modelled function $H'_{X,U}(f)$.
- f) Based on the calculated force factor T_{Bl} , the identified quality factor Q_{ES} , the resonance frequency f_s and the DC resistance R_E , the compliance C_{MS} shall be calculated using Formula (1).
- g) The resistance R_{MS} shall be calculated based on the measured quality factor Q_{MS} using the relationship in Formula (2).

- h) Based on the compliance C_{MS} , the moving mass M_{MS} shall be calculated using the relationship in Formula (3).

20.5 Pure lumped mechanical parameters

20.5.1 General

The fundamental vibration mode of the transducer operated in vacuum shall be described by a lumped parameter model generating the mechanical impedance given in Formula (8):

$$\underline{Z}_{MD}(f) = \frac{\underline{E}(f, \mathbf{r}_{coil})}{j2\pi f \underline{X}(f, \mathbf{r}_{coil})} = \frac{T_{BI}^2}{\underline{Z}_{EMD}(f)} = \frac{1}{j2\pi f C_{MD}(f)} + R_{MD}(f) + j2\pi f M_{MD} \quad (8)$$

which is inversely related to the electrical impedance $\underline{Z}_{EMD}(f)$ representing the mechanical resonance in the electrical domain scaled by the squared force factor T_{BI}^2 . The lumped parameter M_{MD} represents the moving mass without air load. At low frequencies, the compliance $C_{MD}(f)$ of the mechanical suspension (which is the inverse of the stiffness $K_{MD}(f)$), and the mechanical resistance $R_{MD}(f)$ also become dependent on the visco-elasticity of the material.

NOTE In order to distinguish between the pure mechanical parameters and the lumped parameters of the transducer with air load, the character 'D' replaces the character 'S' in the subscript.

20.5.2 Method of measurements

- The electrical impedance $\underline{Z}_E(f)$ of the DUT operated in vacuum shall be measured in accordance with Clause 18.
- The measurement of the pure mechanical parameters of the transducer operated in vacuum shall be performed by using either the laser or the added mass method in accordance with 20.4.2.4 and 20.4.2.2, respectively.

The relative lumped parameters shall be calculated in accordance with 20.3 using the character "D" in the subscript of the parameter to indicate the measurement in vacuum.

NOTE A useful approximation of the moving mass found in vacuum can be calculated using $M_{MD} = M_{MS} - 1,7 \rho_0 \pi a^3$ given the total moving mass M_{MS} of a transducer having a round radiator of radius a operated in an infinite baffle with air load, see Beranek [4].

20.6 Compliance versus frequency

20.6.1 General

The mechanical compliance $C_{MS}(f)$ and $C_{MD}(f)$ of the suspension shall be presented versus frequency in the range where the reactive part of the mechanical impedance is not dominated by the moving mass (for example $f < 2f_s$).

20.6.2 Method of measurements

- While operated in a vacuum, the mechanical transfer function $\underline{H}_X(f)$ of the device under test shall be measured in accordance with 19.6.

The visco-elasticity by definition is a mechanical property and should be separated from other properties that can influence or increase the compliance $C_{MS}(f)$ at lower frequencies $f < f_s$ such as an air cavity inside the transducer.

- The mechanical transfer function $\underline{H}_X(f)$ shall be modelled using a visco-elastic model presented by Knudsen [10] or Ritter [11].

The 3-parameter creep model as proposed by Ritter [11] is recommended as shown:

$$C_{MD}(f) = C_{min} \left(1 - \kappa \lg_{10} \left(\frac{(f/f_{min})}{\sqrt{1+(f/f_{min})^2}} \right) \right)$$

where the minimum compliance C_{min} and the factor κ describe the slope of the compliance curve below a minimum frequency f_{min} .

- c) The free parameters of the selected visco-elastic model shall be estimated by minimizing the error between measured and modelled mechanical transfer function $\underline{H}_X(f)$.
- d) The mechanical compliance $C_{MD}(f)$ of the transducer operated in vacuum shall be calculated based on the selected creep model with the estimated parameters. The manufacturer shall present either $C_{MD}(f)$ versus frequency or the free parameters along with a comprehensive definition of the model used.

NOTE For frequencies f far below the resonance frequency f_s , the slope of the compliance $C_{MS}(f)$ corresponds with the slope of the mechanical transfer function $\underline{H}_X(f)$.

- e) The compliance $C_{MS}(f)$ of the transducer operated in free air shall be calculated using Formula (9)

$$C_{MS}(f) = 1 / [1/C_{MD}(f) + 1/C_{MS}(f_s) - 1/C_{MD}(f_s)] \quad (9)$$

where the compliance $C_{MS}(f_s) = C_{MS}$ is a lumped parameter identified in accordance with 20.4.

20.7 Distributed mechanical parameters

20.7.1 Receptance

20.7.1.1 General

The receptance is the mechanical transfer function $\underline{H}_{X,F}(f, \mathbf{r}_r) = \underline{X}(f, \mathbf{r}_r) / \underline{F}(f)$ between the transducer's excitation force $F(f)$ and the displacement $\underline{X}(f, \mathbf{r}_r)$ at the point $\mathbf{r}_r$ on the radiator's surface. The receptance shall be measured under small-signal conditions at a sufficient spatial resolution to represent the mode shape in the frequency range of interest.

NOTE The receptance $\underline{H}_{X,F}(f, \mathbf{r}_r)$ is the basis for modal analysis of the mechanical vibrations on the surface of the radiator. The results from numerical simulations (FEA) and laser vibrometry can be used for comparison.

20.7.1.2 Methods of measurement

- a) Measure the electrical input impedance $\underline{Z}_E(f)$ of the device under test operated in free air under small-signal conditions in accordance with Clause 18.
- b) The transfer function $\underline{H}_{X,U}(f, \mathbf{r}_r)$ between terminal voltage and displacement on the radiator's surface at the scanning points $\mathbf{r}_r[n]$ for $0 \leq m \leq M$ shall be measured in accordance with 19.6 with sufficient spatial resolution ($M > 100$ scanning points).
- c) The force factor T_{BI} is determined in accordance with 20.4.
- d) The receptance $\underline{H}_{X,F}(f, \mathbf{r}_r)$ shall be calculated at all scanning points $\mathbf{r}_r[m]$ for $0 \leq m \leq M$ using Formula (10):

$$\underline{H}_{X,F}(f, \mathbf{r}_r) = \underline{H}_{X,U}(f, \mathbf{r}_r) \frac{\underline{Z}_E(f)}{T_{BI}} \quad (10)$$

20.7.2 Modal analysis

20.7.2.1 General

Modal analysis (see Bright [12]) shall be applied to the receptance $\underline{H}_{X,F}(f, \mathbf{r}_r)$ measured at a sufficient number of scanning points $\mathbf{r}_r[i]$ with $0 \leq m \leq M$ to reveal the following expansion:

$$\underline{H}_{X,F}(f, \mathbf{r}_r) = \sum_{n=0}^N \underline{H}_n(f, \mathbf{r}_r) = \sum_{n=0}^N \frac{\alpha_n \Phi_n(\mathbf{r}_r)}{1 + \eta_n \left(\frac{2\pi f}{\omega_n} \right) j - \left(\frac{2\pi f}{\omega_n} \right)^2} \quad (11)$$

with modal parameters: mode shape represented as orthonormal Eigenvectors $\Phi_n(\mathbf{r}_r)$, natural frequency ω_n , modal loss factor η_n and modal gain α_n of the n^{th} order mode.

NOTE Each dominant mode found in the modal expansion of $\underline{H}_{X,F}(f, \mathbf{r}_r)$ is a distinct resonance at the natural frequency ω_n in the accumulated acceleration level in accordance with 19.7. The relative 3 dB bandwidth of the resonance corresponds to the modal loss factor η_n . These modal parameters are the basis for fitting the FEA model using estimated frequency dependent material parameters in the mechanical components, such as the Young's modulus $\underline{E}(f)$, to the laser vibrometer measurement results of the DUT.

20.7.2.2 Method of measurements

- a) Measure the receptance $\underline{H}_{X,F}(f, \mathbf{r}_r[m])$ at a sufficient number of scanning points $\mathbf{r}_r[m]$ for $0 \leq m \leq M$ on the surface of the radiator in accordance with 20.7.1.

NOTE The number of scanning points depends on the targets of the modal analysis. The evaluation of rocking modes and the identification of the root causes requires typically less than 20 points while the evaluation of modes at higher frequencies may require more than 500 points.

- b) Perform a singular value decomposition on the receptance $\underline{H}_{X,F}(f, \mathbf{r}_r[m])$ to separate the orthogonal modes, find the mode shapes $\Phi_n(\mathbf{r}_r)$ and determine the modal frequency response $\underline{H}_n(f)$.
- c) Estimate the natural frequency ω_n , the modal loss factor η_n and the modal gain α_n of n^{th} order mode in Formula (11).

20.7.3 Relative rocking level

20.7.3.1 General

The relative rocking level $R_{\text{REL},n}$ is defined as the difference between the accumulated acceleration level $L_{\text{AA},n}$ of the n^{th} order rocking mode with $n = 1, 2$ and the $L_{\text{AA},0}$ of the piston mode ($n = 0$), or it can be approximated (see Cardenas [14]) as follows:

$$\begin{aligned} R_{\text{REL},n}(f_n) &= L_{\text{AA},n}(f_n) - L_{\text{AA},0}(f_n) \\ &\approx 20 \lg_{10} \left(\frac{\int_{S_r} |\underline{H}_n(f_n, \mathbf{r}_r)| dS}{\int_{S_r} |\underline{H}_0(f_n, \mathbf{r}_r)| dS} \right) \end{aligned} \quad (12)$$

20.7.3.2 Method of measurements

- a) Measure the receptance $\underline{H}_{X,F}(f, \mathbf{r}_r[m])$ at sufficient scanning points $\mathbf{r}_r[m]$ for $0 \leq m \leq M$ on the surface of the radiator in accordance with 20.7.1.
- b) Perform a modal analysis in accordance with 20.7.2 and select the receptance $\underline{H}_n(f, \mathbf{r}_r)$ with $n = 0, 1, 2$. Determine the natural frequency $\omega_n = 2\pi f_n$ of the first and second order rocking modes ($n = 1, 2$).

- c) Calculate the relative rocking level $R_{REL,n}(f_n)$ at the natural frequencies f_n with $n = 1, 2$ according to Formula (12).

NOTE A relative rocking level $R_{REL,n}(f_n)$ larger than –5 dB indicates significant rocking in the radiator that can cause impulsive distortion, such as voice-coil rubbing. The impulsive distortion can be measured using the method defined in IEC 60268-21.

20.7.4 Centre of gravity

20.7.4.1 General

The centre of gravity with respect to the pivot point shall be measured in Cartesian coordinates (y_{CG}, z_{CG}) or in polar coordinates (d_M, γ_M) .

NOTE An imbalance in the moving parts of the transducer can be caused by asymmetrical mass distribution with respect to the pivot point (see Klippel [13]). The pivot point is the cross point of the nodal lines between the first and second order rocking modes and corresponds with the origin of the coordinate system as shown in Figure 4. The asymmetrical distribution could be caused by component thickness variations, non-homogenous glue distribution etc. If the centre of gravity is not located at the pivot point ($y_{CG} \neq 0, z_{CG} \neq 0$), the translational displacement and the tilting angles will generate moments exciting the first and second order rocking modes. The distance d_M between the centre of gravity point and the pivot point shows the magnitude of the imbalance and the angle γ_M reveals the direction of the imbalance.

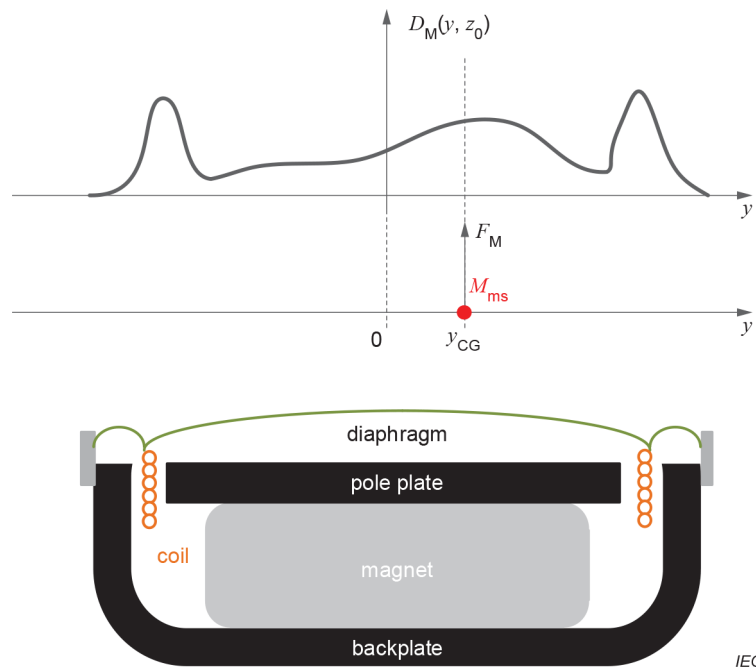


Figure 4 – Asymmetrical mass distribution function $D_M(y, z_0)$ in the mechanical system of a microspeaker that shifts the centre of gravity away from the pivot point

20.7.4.2 Method of measurements

- Measure the receptance $\underline{H}_{X,F}(f, \mathbf{r}_r[m])$ at sufficient scanning points $\mathbf{r}_r[i]$ for $0 \leq m \leq M$ on the surface of the radiator in accordance with 20.7.1.
- Perform a modal analysis in accordance with 20.7.2 and select the modal transfer functions $\underline{H}_n(f, \mathbf{r}_r)$ with $n = 0, 1, 2$. Determine the mode shape $\Phi_n(\mathbf{r}_r)$, the natural frequency ω_n , the modal loss factor η_n , the modal gain α_n of the piston mode ($n = 0$) and the modal gains α_n of the two rocking modes ($n = 1, 2$).
- Fit the lumped parameter model developed for rocking modes as described in [13] to the modal analysis result data.
- Calculate the coordinates of the centre of gravity based on the identified parameters of the rocking mode model according to Cardenas [14].