IEC 62459

INTERNATIONAL STANDARD

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Sound system equipment – Electroacoustical transducers – Measurement of suspension parts

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INTERNATIONAL ELECTROTECHNICAL COMMISSION
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SOUND SYSTEM EQUIPMENT –
ELECTROACOUSTICAL TRANSDUCERS –
MEASUREMENT OF SUSPENSION PARTS

FOREWORD

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International Standard IEC 62459 has been prepared by IEC technical committee 100: Audio, video and multimedia systems and equipment.

This first edition cancels and replaces the IEC/PAS 62459 published in 2006. It constitutes a technical revision. The main changes are listed below:

– descriptions of the methods of measurement are adjusted to the state of the technology;

– addition of Clauses 5 to 13;

– integration of Annex A "Code of practice" at the main part of the standard;

– overall textual review.

The text of this standard is based on the following documents:

FDIS	Report on voting
100/1625/FDIS	100/1648/RVD

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

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

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

• reconfirmed,
• withdrawn,
• replaced by a revised edition, or
• amended.

A bilingual version of this publication may be issued at a later date.

The contents of the corrigendum of November 2011 have been included in this copy.

IMPORTANT – The "colour inside" logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this publication using a colour printer.

INTRODUCTION

The properties of the suspension parts such as spiders and surrounds have a significant influence on the final sound quality of the loudspeaker. This International Standard defines measurement methods and parameters required for development and quality-assurance by suspension-part manufacturers and loudspeaker manufacturers.

Static and dynamic methods have been developed for measuring the suspension parts at small and high amplitudes. Due to the visco-elastic properties of the suspension material (fabric, rubber, foam, paper) the measurement results depend on the measurement conditions and are not comparable between different methods. For example, the properties measured by static method significantly deviate from the dynamic behaviour of the suspension material when excited by an audio signal. This standard defines the terminology, the characteristics which should be specified and the way the results should be reported. The goal is to improve the reproducibility of the measurement, to simplify the interpretation of the results and to support the communication between manufacturers of suspension parts and complete drive units.

<div align="center">

**SOUND SYSTEM EQUIPMENT –
ELECTROACOUSTICAL TRANSDUCERS –
MEASUREMENT OF SUSPENSION PARTS**

</div>

1 Scope

This International Standard applies to the suspension parts of electroacoustic transducers (for example, loudspeakers). It defines the parameters and measurement method to determine the properties of suspension parts like spiders, surrounds, diaphragms or cones before being assembled in the transducer. The measurement results are needed for engineering design purposes and for quality control. Furthermore, this method is intended to improve the correlation of measurements between suspension-part manufacturers and loudspeaker manufacturers.

The measurement methods provide parameters based on linear and nonlinear modelling of the suspension part and uses both static and dynamic techniques.

2 Normative references

The following referenced documents are indispensable for the application 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 60268-1, *Sound system equipment – Part 1: General*

3 Terms and definitions

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

**3.1
suspension part**
surround of the cone made of rubber, foam, paper and fabric and the spider which is usually made out of impregnated fabric

**3.2
displacement**
x
perpendicular direction at the inner rim of the suspension part

**3.3
peak displacement**
x_{peak}
peak value of the displacement occurring during a dynamic measurement at resonance frequency

**3.4
driving force**
F
total effect of the restoring force, friction and inertia of both the suspension part and the inner clamping parts at the neck of the suspension

3.5
transfer function
H(f)
amplitude response given by

$$H(f) = \frac{|X(j\omega)|}{|F(j\omega)|} \tag{1}$$

between the displacement spectrum $X(j\omega) = FT\{x(t)\}$ and the force spectrum $F(j\omega) = FT\{F(t)\}$

3.6
dynamic stiffness
$K(x_{\text{ac}})$
reciprocal of the dynamic compliance $C(x_{\text{ac}})$; it is the ratio of instantaneous force F_{ac} to instantaneous displacement x_{ac}, for an a.c. excitation signal at point x_{ac}, given by the following equation

$$K\left(x_{\text{ac}}\right) = \frac{1}{C(x_{\text{ac}})} = \frac{F_{\text{ac}}}{x_{\text{ac}}} \tag{2}$$

NOTE   The dynamic stiffness $K(x_{\text{ac}})$ corresponds to the secant between origin and working point defined by x_{ac} in the force-displacement curve.

3.7
incremental stiffness
$K_{\text{inc}}(x_{\text{dc}})$
reciprocal of the incremental compliance $C_{\text{inc}}(x_{\text{dc}})$; it is the ratio of a small a.c. force F_{ac} to the small a.c. displacement x_{ac} produced by it at working point x_{dc} under steady-state condition as given by the following equation

$$K_{\text{inc}}\left(x_{\text{dc}}\right) = \frac{1}{C_{\text{inc}}(x_{\text{dc}})} = \frac{F_{\text{ac}}}{x_{\text{ac}}} \tag{3}$$

NOTE   The incremental stiffness $K_{\text{inc}}(x_{\text{dc}})$ corresponds to the gradient at the working point defined by x_{dc} in the force-deflection curve.

3.8
static stiffness
$K_{\text{static}}(x_{\text{dc}})$
reciprocal of the static compliance $C_{\text{static}}(x_{\text{dc}})$; it is the ratio of a d.c. force F_{dc} and the d.c. displacement x_{dc} produced by it at the working point x_{dc} under steady-state condition; the static stiffness $K_{\text{static}}(x_{\text{dc}})$ corresponds to the secant between origin and working point in the force-displacement curve, given by the following equation

$$K_{\text{static}}\left(x_{\text{dc}}\right) = \frac{1}{C_{\text{static}}(x_{\text{dc}})} = \frac{F_{\text{dc}}}{x_{\text{dc}}} \tag{4}$$

3.9
moving mass
m
defined by

$$m = \delta m_{\text{s}} + m_{\text{c}} \tag{5}$$

where
m_{s} is the mass of the suspension part,
m_{c} is the additional mass of the inner clamping parts,
δ is the clamping factor (with $0 < \delta \leq 1$), describing the fraction of the suspension which contributes to the moving mass.

NOTE   If factor δ is not known, the moving mass is approximated by using the total weight of the suspension part ($\delta = 1$) and ensuring that the mass, m_C, of the inner clamping part dominates the moving mass, m ($m_C \gg m_S$).

3.10
resonance frequency
f_R
frequency of an a.c. displacement x_{ac} at which the restoring force, $F_K = K(x_{ac})x_{ac}$ of the suspension part equals the inertia of the moving mass, m, given by the following equation

$$F_K = K(x_{ac})x_{ac} = m\frac{d^2 x_{ac}}{dt^2} \tag{6}$$

3.11
lowest cone resonance frequency
f_0
frequency at which the cone mass and suspension stiffness resonate

NOTE   The lowest cone resonance frequency can be approximated by

$$f_0 \approx \frac{1}{2\pi}\sqrt{\frac{K(x_{off})}{\delta m_S}} \tag{7}$$

using the stiffness $K(x_{off})$ at the offset x_{off} due to gravity, the clamping factor δ and the cone mass m_S.

3.12
effective stiffness
K_{eff}
stiffness given by

$$K_{eff}(x_{peak}) = (2\pi f_R)^2 m \tag{8}$$

describing the conservative properties of the suspension part performing a vibration at the resonance frequency, f_R, using the moving mass, m

NOTE   The effective stiffness, $K_{eff}(x_{peak})$, or the reciprocal, compliance, $C_{eff}(x_{peak}) = 1/K_{eff}(x_{peak})$, are integral measures of the corresponding non-linear parameters, $K(x)$ and $C(x)$, in the working range used, defined by the peak value, x_{peak}. The effective parameters are directly related to the resonance frequency and may be measured with minimal equipment. However, the effective parameters can only be compared if the measurements are made at the same peak displacement, x_{peak}.

3.13
loss factor
Q
factor estimated by the ratio

$$Q = \frac{|H(f_R)|}{|H(f_{dc})|} \tag{9}$$

between the magnitude of the transfer function, $H(f_R)$, at resonance frequency, f_R, and the magnitude of the transfer function, $H(f_{dc})$, at very low frequencies, f_{dc} (with $f_{dc} \ll f_r$).

NOTE   If the losses are sufficiently high ($Q > 2$), the transfer function, $H(f)$, has a distinct maximum (peak) at the resonance frequency, f_R.

3.14
mechanical resistance
R
given by

$$R = \frac{2\pi f_R m}{Q} \tag{10}$$

where

m   is the moving mass,

f_R is the resonance frequency f_R,

Q is the Q-factor.

3.15
inner clamp dimension
D_i
diameter at the neck of the suspension part which is clamped by inner clamping parts (for example, cone and cap)

3.16
outer clamp dimension
D_o
inner diameter of the outer rim of the suspension part which is clamped by the outer clamping parts (for example, the upper and lower clamping rings)

4   Test conditions

The test should be made at 15 °C to 35 °C ambient temperature, preferably at 20 °C, 25 % to 75 % relative humidity and 86 kPa to 106 kPa air pressure, as specified in IEC 60268-1.

Prior to the measurement the suspension part under test should be stored under these climatic conditions for 24 h.

5   Clamping of the suspension part

5.1   General

The suspension part should be clamped during the dynamic testing in a similar way as mounted in the final loudspeaker.

5.2   Destructive measurement

In some cases, it may be convenient to use adhesive and original loudspeaker parts (voice coil former, frame) for clamping.

5.3   Non-destructive measurement

However, non-destructive testing is preferred for comparing samples, storing reference units and for simplifying communication between manufacturer and customer. Since tooling of special clamping parts fitted to the particular geometry of the suspension is costly and time-consuming, a more universal clamping system comprising a minimal number of basic elements (for example, rings, caps and cones) may be preferred.

The moving mass, m, depends on the mass of the moving parts of the suspension, the air load and the mass of the inner clamping parts. If the mass of the inner clamping part is much higher than the mass of the suspension, the total moving mass, m, can be approximated by the total weight of the suspension together with inner clamping parts, $(\delta = 1)$. In this case, the mass of the clamped areas at the outer rim of the suspension and the influence of the air load can be neglected.

5.4   Clamping position

A vertical position of the suspension part during measurement (displacement in horizontal direction) is mandatory if the weight of the inner clamping parts or the weight of the suspension part is not negligible. A horizontal position (displacement in vertical direction) may cause an offset in cone displacement due to gravity, giving a higher stiffness value.

5.5   Guiding the inner clamping part

An additional guide for the inner clamping parts may be used to prevent eccentric deformation or tilting of the suspension and to suppress other kinds of vibration (rocking modes).

5.6   Reporting the clamping condition

The clamping factor according 3.9 shall also be stated; if not, the default value, $\delta = 1$, is used. It is strongly recommended that the inner clamping dimension, D_i, and the outer clamping dimension, D_o, as well as the geometry of the inner clamping parts be reported. The orientation of the suspension part (which side of the suspension part is used as front and back side in the measurement jig) should also be reported. The repeatability of the measurement can be improved by using the same clamping parts and the same orientation of the suspension.

6   Methods of measurement

6.1   Static measurement

This technique for measuring the static stiffness according to Equation (4) uses a d.c. signal of certain magnitude (for example, a constant force F_{dc}) as stimulus and measures a d.c. response of the suspension part (for example, the displacement x_{dc}) under steady-state condition. The measurement time required to get a steady-state response depends on the visco-elastic behaviour of the suspension material (creep) which is usually much longer than the settling time for an a.c. signal corresponding to the resonance frequency f_R.

6.2   Quasi-static measurement

This technique is similar to the static measurement as described in 6.1, using a relatively short measurement time T. The ratio of d.c. force F_T and d.c. displacement x_T is the quasi-static stiffness $K_{quasi}(x_T)$ at the working point x_T. Since the suspension part has not reached the final equilibrium the quasi-static stiffness is usually higher than the static stiffness ($K_{quasi}(x) > K_{static}(x)$). Settling/reading-time that has a great influence on the results shall be stated with the results.

6.3   Incremental dynamic measurement

This technique for measuring the incremental stiffness $K_{inc}(x_{dc})$ according to Equation (3) uses a superposition of a d.c. signal of certain magnitude (for example, constant restoring force F_{dc} generating a d.c. position x_{dc}) and a small a.c. signal (e.g. restoring force F_{ac}) as stimulus and measures the a.c. response of the suspension part (e.g. the a.c. part of the displacement x_{ac}) under steady-state conditio. Neglecting the visco-elastic behaviour of the suspension material, the incremental stiffness, $K_{inc}(x_i)$ can be transformed into the regular stiffness $K(x)$ by

$$K(x) = \frac{1}{x}\int_0^x K_{inc}(x)dx \tag{11}$$

6.4   Full dynamic measurement

This technique for measuring the dynamic stiffness $K(x_{ac})$ uses an a.c. signal of certain magnitude (for example, the a.c. restoring force F_{ac}) and measures the a.c. response of the suspension part (for example, a displacement x_{ac}).

7 Static displacement $x_{static}(F_{dc})$

7.1 Characteristic to be specified

Static displacement $x_{static}(F_{dc})$ is the difference of the position of the inner clamping part caused by d.c. force F_{dc} under steady-state condition.

7.2 Method of measurement

7.2.1 General

The static displacement can be measured by generating the d.c. force F_{dc} by the weight of a known mass attached to the inner clamping part, as shown in Figure 1. This technique can also be automated by using step motors with servo control to induce a displacement or force.
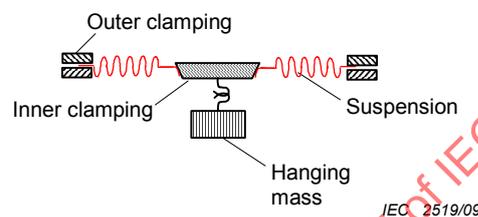

Outer clamping
Inner clamping
Suspension
Hanging mass
IEC 2519/09

Figure 1 – Measurement of static displacement

7.2.2 Test equipment

The test equipment shall consist of:

- a fixture and associated elements to position the suspension part in the horizontal position while performing a fixed clamping of the outer rim (for example using rings) as shown in Figure 1;

- a cap or plug which fits to the neck of the suspension part and provides means for inducing a defined force in the vertical direction. When using the 'hanging mass method' (see Figure 1), the cap shall provide a hook for holding an additional mass;

- means for generating a defined force in the vertical direction;

- a sensor for measuring the displacement of the suspension. An optical displacement sensor (laser) is preferable to a mechanical or electrical sensor.

7.2.3 Procedure

The measurement is performed by the following steps:

a) the outer rim of the suspension part is clamped at the outer dimension, D_o, by using the top and bottom clamp rings;

b) the cap is set on the neck of the suspension part;

c) the position x_{init} of the cap is measured;

d) a defined force is applied to the cap. The suspension part is checked for any abnormal deformation such as creasing, cocking, corrugation inversion, if necessary the force is reduced;

e) the displacement x_{mass} is measured after a defined settling time (T = 5 s) to measure the static or quasi-static behaviour;

f) the difference $x_{static} = x_{mass} - x_{init}$ is calculated;

g) the suspension part is flipped over and a second measurement with a deflection in the other direction is performed while using a proper clamping part which considers the shape of the suspension.

NOTE The Automated Induced Displacement Technique and the Hanging Mass Technique are described in greater detail in [5][1]).

7.2.4 Presentation of results

The results of the 'hanging mass method' shall be reported as displacement x_{static} for a given attached mass, for example x_{static} = 5 mm with m = 50 g.

The results of an automated technique which performs a series of measurement where the magnitude and sign of the induced force F_{dc} is changed, are preferably presented as a curve showing force versus displacement.

NOTE The static displacement x_{static} depends greatly on the measurement time T, the initial conditions and other visco-elastic behaviour of the material (creep), causing a hysteresis in the force-displacement curve.

8 Static stiffness $K_{static}(x_{static})$

8.1 Characteristic to be specified

Static stiffness $K_{static}(F_{dc})$ is the ratio between static force F_{dc} and static displacement x_{dc} under steady-state condition.

8.2 Method of measurement

The static displacement x_{dc} is measured according to 7.2 and the static stiffness K_{static} is calculated according to Equation (4).

Using the 'hanging mass technique', the static stiffness (see equation below)

$$K_{static}\left(x_{dc}\right) = \frac{g m_{add}}{x_{dc}}$$ (12)

is calculated by using the standard gravity constant g = 9,81 m/s^2 and the known mass m_{add} attached to the inner clamping part (such as m_{add} = 50 g).

NOTE There are usually significant differences between the static stiffness and the dynamic stiffness which describes the behaviour of the suspension part with an audio signal.

8.3 Presentation of results

The results of the 'hanging mass method' shall be reported as static stiffness K_{static} for a given attached mass, for example K_{static} = 5 N/mm with m_{add} = 50 g.

The results of the automated technique which performs a series of measurements where the magnitude and sign of the induced force F_{dc} is changed is preferably presented as a curve showing static stiffness $K_{static}(x_{dc})$ versus displacement x_{dc}.

9 Lowest cone resonance frequency, f_0

9.1 Characteristic to be specified

The lowest cone resonance frequency f_0 is the lowest resonance frequency of a loudspeaker cone clamped at the outer rim (usually the surround) in the horizontal position, using no inner

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[1] Numbers in square brackets refer to the Bibliography.

clamping part. The lowest cone resonance frequency is defined as the frequency where the transfer function $H(f)$ according to Equation (1) has a distinct maximum (peak).

9.2 Method of measurement

9.2.1 General

The cone can be excited acoustically by using an additional loudspeaker mounted below the cone, as illustrated in Figure 2. The resonance frequency can be measured dynamically by using an acoustical excitation.

NOTE   This technique is less suited to measure the stiffness K of the surround because the clamping factor δ is not known. The lowest cone resonance f_0 may depend on the amplitude of the excitation signal due to the nonlinearity of the surround and should be interpreted as an effective parameter. The weight of the cone may also cause offset x_{off} which generates a higher stiffness than found at the rest position $x = 0$.

9.2.2 Test equipment

The essential elements of test equipment needed are as follows:

- a sine wave generator and frequency counter;

- a power amplifier;

- a driving loudspeaker (usually a large woofer) for acoustical excitation of the cone, having a free air resonance below one third of the resonance frequency of the cone to be tested. The driving loudspeaker shall be mounted on a square solid plate parallel to the lower clamp ring surface such that the face of the mounting plate is 0,09 to 0,1 m from the test cone mounting surface. The area between the driving loudspeaker mounting plate and the lower clamp ring shall be open on each side to prevent undesirable loading of the driving loudspeaker. This amounts to testing within the driving loudspeaker's unbaffled near field;

- an upper and a lower clamp ring to firmly clamp the cone;

- an optical or acoustical sensor for detecting the resonance of the clamped cone. Visual detection is not recommended.
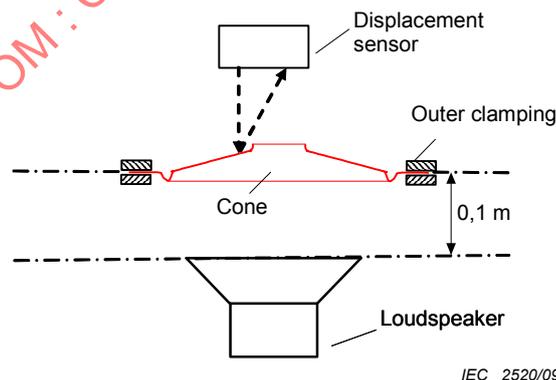

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Figure 2 – Measurement of lowest cone resonance f_0

9.2.3 Procedure

Proceed as follows:

   a) the test cone is placed between properly matched clamp rings;

   b) the sinusoidal signal is supplied via the power amplifier to the loudspeaker;

   c) the resonance frequency is measured where the maximum excursion of the cone vibration is observed.

NOTE   This technique is described in greater detail in reference [4].

9.2.4   Presentation of results

It is recommended to report the lowest resonance frequency f_0 in Hz together with ambient conditions (such as humidity and temperature).

10   Dynamic stiffness $K(x_{ac})$

10.1   Characteristic to be specified

The dynamic stiffness $K(x_{ac})$ is the ratio of instantaneous force F_{ac} and instantaneous displacement x_{ac} for an a.c. excitation signal under steady-state.

NOTE   A full dynamic measurement of the linear and nonlinear parameters of the suspension part is required to explain the behaviour of the suspension in the assembled loudspeaker excited by an audio signal.

10.2   Method of measurement

10.2.1   General

The suspension part is firmly clamped at the outer rim and the a.c. excitation force is induced at the inner neck of the suspension. The suspension part should be in the vertical position during measurement (producing a displacement in horizontal direction) to avoid any bias due to weight. Those requirements can be realized by operating the suspension part at the resonance frequency f_R determined by using the moving mass m and the dynamic stiffness K according to Equation (6). It is recommended to excite the resonator by an a.c. sound pressure signal generated by a loudspeaker mounted in an enclosure, as shown in Figure 3. This technique can be applied to most kinds of suspensions (spiders and cones).

10.2.2   Test equipment

The acoustical excitation methods as shown in Figure 3 use the following elements:

a) means for generating a signal used as stimulus (for example, sine wave generator);

b) a power amplifier;

c) means for exciting the suspension part by the stimulus (for example, a loudspeaker mounted in a sufficiently large test box for acoustical excitation, as shown in Figure 3);

d) outer clamping parts (for example, a pair of matched clamping rings to clamp the rim of the suspension part);

e) inner clamping parts (for example, a cone and a cap) to apply the driving force at the inner neck of the suspension similar to the final usage in the assembled loudspeaker;

f) means for ensuring a displacement in normal direction of the suspension part (for example a guiding rod) to avoid any rocking modes of the suspension part at high amplitudes. The friction of the inner clamping part on the guiding rod should be sufficiently low by using an appropriate design (e.g. Teflon bearing on the sleeve and polished surface of the rod) to get a resonator having a Q-factor > 2.

g) means for determining the displacement and force at the suspension part by performing a direct (mechanical) or indirect (acoustical) measurement. If the loudspeaker is excited acoustically, the driving force, $F(t)$, may be calculated from the sound pressure, $p(t)$, measured inside the enclosure.
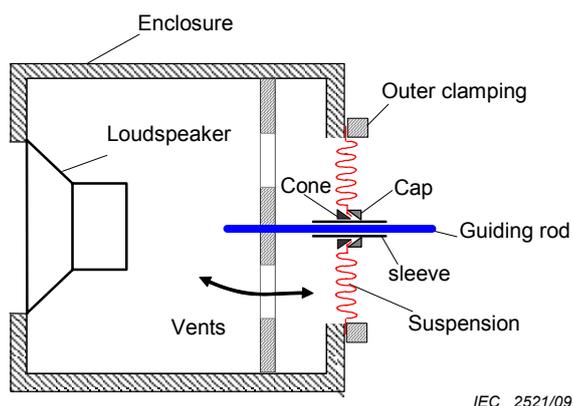
h) a precision balance.

IEC 2521/09

Figure 3 – Pneumatic excitation of the suspension part

10.2.3 Procedure

Both the effective stiffness, K_{eff}, and the displacement varying stiffness, $K(x)$, of the suspension part are measured dynamically by performing the following steps:

a) the neck of the suspension part is clamped at the inner dimension, D_i, by using inner clamping parts (for example, a cap and a cone);

b) the total mass of the suspension and inner clamping parts are measured by using a precision balance;

c) the outer rim of the suspension part is clamped at the outer dimension, D_o, by using top and bottom clamp rings. The cap is mounted on the upper side while the cone is on the lower side. It is recommended that the upper side of the suspension part which points to positive displacement is marked. The measurement of the nonlinear stiffness $K(x)$ requires a guiding rod for the inner clamping part;

d) the suspension part is excited (for example, pneumatically) by using a sinusoidal sweep starting at $f_s = 0.8 \times f_R$ and ending at frequency $f_e = 1.2 \times f_R$. During the sweep, the displacement, $x(t)$, and the total driving force, $F(t)$, at the suspension part are measured versus time;

e) the transfer function, $H(f) = X(f)/F(f)$, is calculated from the FFT displacement spectrum, $X(f) = \mathrm{FT}\{x(t)\}$, and force spectrum, $F(f) = \mathrm{FT}\{F(t)\}$;

NOTE   The measurement of the driving force, $F(t)$, may be omitted under certain conditions. If the test enclosure used for acoustical excitation has a large volume and the acoustical compliance, C_{ab}, of the enclosed air is much larger than the equivalent acoustical compliance of the suspension part under test, the driving force, $F(j\omega)$, becomes almost constant and the transfer function, $H(f) \approx |X(j\omega)|$, can be approximated by the amplitude response of the measured displacement. Thus, the sound-pressure measurement may be omitted for spiders and cones with sufficiently small diameter operated in a large enclosure (D_o less than 200 mm for 100 l air volume).

f) The loss factor, Q, is determined by using Equation (9). If the loss factor $Q > 2$, the resonance frequency, f_R, equals the frequency at which the transfer function, $H(f)$, has a distinct maximum as shown in Figure 4.

g) The non-linear stiffness, $K(x)$, is calculated from the measured displacement time signal, $x(t)$, and force, $F(t)$, by using a non-linear system identification technique [6].
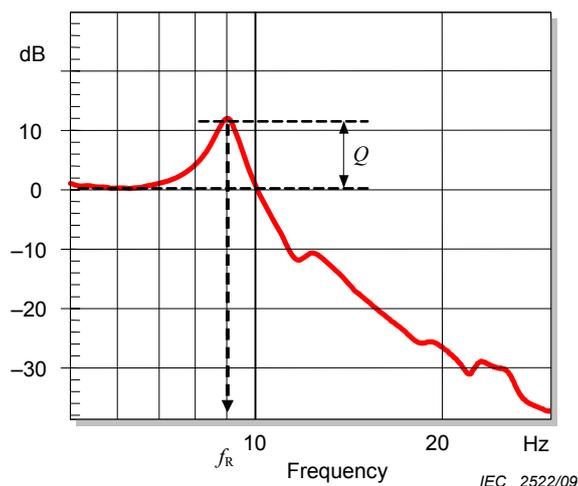
**Figure 4 – Magnitude response of the normalized
transfer function, $H(f)/H(0)$, versus frequency, f**

10.2.4 Presentation of results

The non-linear stiffness, $K(x)$, may be reported preferably as a curve showing stiffness, $K(x)$, versus displacement, x. Positive displacement, x, corresponds to a deflection of the suspension toward the side where the cap is clamped.

11 Coefficients of the power series expansion of $K(x)$

11.1 Characteristics to be specified

The coefficients k_i with $i = 0, 1, …, N$ of the power series expansion of the dynamical stiffness, defined by

$$K(x) = \sum_{i=0}^{N} k_i x^i .$$

(13)

11.2 Presentation of results

The dynamic stiffness is measured according to Clause 10. The coefficients k_i are reported together with the maximal peak displacement x_{peak} occurring during the dynamical measurement.

12 Effective stiffness $K_{eff}(x_{peak})$

12.1 Characteristic to be specified

The effective stiffness $K_{eff}(x_{peak})$ is defined by the resonance frequency f_R and the moving mass m according to Equation (8).

12.2 Method of measurement

The dynamic measurement technique as described in Clause 9 is used to measure the resonance frequency f_R.