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Mechanical vibration and shock — Experimental determination of mechanical mobility —

Part 5: Measurements using impact excitation with an exciter which is not attached to the structure

Vibrations et chocs mécaniques — Détermination expérimentale de la mobilité mécanique —

Partie 5: Mesurages à partir d'une excitation par choc appliquée par un excitateur non solidaire de la structure

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*.

This second edition cancels and replaces the first edition (ISO 7626-5:1994), which has been technically revised.

The main changes compared with the previous edition are as follows:

— updating of normative and informative references in the bibliography;

— redrawing of figures and graphs.

A list of all parts in the ISO 7626 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

0.1 General introduction to the ISO 7626 series on mobility measurement

Dynamic characteristics of structures assumed to behave linearly can be determined as a function of frequency from mobility measurements or measurements of the related frequency-response functions (FRF), known as accelerance and dynamic compliance. Each of these frequency-response functions is the phasor of the motion response at a point on a structure due to a unit force (or moment) excitation at the same or any other point. The magnitude and the phase of these functions are frequency dependent.

Accelerance and dynamic compliance differ from mobility only in that the motion response is expressed in terms of acceleration or displacement, respectively, instead of velocity. In order to simplify the various parts of the ISO 7626 series, only the term "mobility" will be used. It is understood that all test procedures and requirements described are also applicable to the determination of accelerance and dynamic compliance.

Typical applications for mobility measurements are for:

a) predicting the dynamic response of structures to known or assumed input excitation;

b) determining the modal properties of a structure (natural frequencies, damping ratios and mode shapes);

c) predicting the dynamic interaction of interconnected structures;

d) checking the validity and improving the accuracy of mathematical models of structures;

e) determining the frequency dependent dynamic properties (i.e. the complex modulus of elasticity) of materials.

For some applications, a complete description of the dynamic characteristics can be required using measurements of forces and linear velocities along three mutually perpendicular axes as well as measurements of moments and rotational velocities about these three axes. This set of measurements results in a 6 × 6 mobility matrix for each location of interest. For N locations on a structure, the system thus has an overall mobility matrix of size $6N \times 6N$.

NOTE 1 In general, the measurement directions do not need to be perpendicular to each other, but only their linear independence is needed.

For most practical applications, it is not necessary to know the entire $6N \times 6N$ matrix. Often it is sufficient to measure the driving-point mobility and a few transfer mobilities by exciting with a force at a single point in a single direction and measuring the linear response motions at key points on the structure. In other applications, only rotational mobilities can be of interest.

In order to simplify its use in the various mobility measurement tasks encountered in practice, ISO 7626 is published as a series comprising:

— ISO 7626-1, which covers basic definitions and transducers. The information in ISO 7626-1 is common to most mobility measurement tasks.

— ISO 7626-2, which covers mobility measurements using single-point linear excitation with an attached exciter.

— ISO 7626-5 (this document), which covers mobility measurements using impact excitation with an exciter which is not attached to the structure.

Mechanical mobility is defined as the frequency-response function formed by the ratio of the phasor of the linear or rotational velocity response to the phasor of the applied force or moment excitation. If the response is measured with an accelerometer, conversion to velocity is used to obtain the mobility.

Alternatively, the ratio of acceleration to force, known as accelerance, can be used to characterize a structure. In other cases, dynamic compliance, the ratio of displacement to force, can be used.

NOTE 2 Historically, frequency-response functions of structures have often been expressed in terms of the reciprocal of one of the above-named dynamic characteristics. The arithmetic reciprocal of mechanical mobility has often been called mechanical impedance. However, this is misleading because the arithmetic reciprocal of mobility does not, in general, represent any of the elements of the impedance matrix of the structure. Mobility test data cannot be used directly as part of an analytic impedance model of the structure. To achieve compatibility of the data and the model, the impedance matrix of the model must be inverted to a mobility matrix, or vice versa. This point is elaborated upon in ISO 7626-1:2011, Annex A.

0.2 Introduction to this document

Impact excitation has become a popular method for measuring the frequency response of structures because of its inherent speed and relatively low cost to implement. However, the accuracy of mobility measurements made by using impact excitation is highly dependent upon both the characteristics of the test structure and the experimental techniques employed. With impact excitation, it can be difficult or impossible in certain cases to obtain the accuracy which is attainable using steady state or stationary excitation with an attached exciter, and the impact method carries an increased danger of gross measurement errors[6]. In spite of these limitations, impact testing can be an extremely useful excitation technique when applied properly.

This document provides a guide to the use of impact excitation for mobility measurements. Accurate mobility measurements always require careful attention to equipment selection and to the measurement techniques employed; these factors are especially important when using impact excitation. Furthermore, the characteristics of the test structure, especially its degree of nonlinearity, limit the accuracy which can be achieved. Subclause 4.2 describes these limitations on the use of impact excitation.

Because the exciter is not attached to the structure, this method makes it practical to measure a series of transfer mobilities of a structure by moving the excitation successively to each desired point on the structure, while the response motion transducer remains at a single fixed location and direction. Due to the principle of dynamic reciprocity, such measurements should be equal, assuming linearity, to the results obtained using an attached exciter at the same fixed location and direction with the response transducer relocated to each desired point on the structure. However, it can be difficult to impact the structure in all desired directions at certain locations, and in such cases, it can be more practical to use impact excitation at the fixed location and direction and relocate a multi-axis response transducer to the desired response locations.

NOTE 1 When a multi-axis transducer is used at a fixed location for a modal test and if the impact is applied in one direction of the transducer at each point, then only the mode shape components in that direction are obtained.

NOTE 2 The mass of the multiaxial transducer can change the mass properties of the structure leading to an inconsistent set of measured transfer functions. This can cause serious problems in using the FRFs for experimental modal analysis.

Mechanical vibration and shock — Experimental determination of mechanical mobility —

Part 5: Measurements using impact excitation with an exciter which is not attached to the structure

1 Scope

This document specifies procedures for measuring mechanical mobility and other frequency-response functions of structures excited by means of an impulsive force generated by an exciter which is not attached to the structure under test.

It is applicable to the measurement of mobility, accelerance or dynamic compliance, either as a driving point measurement or as a transfer measurement, using impact excitation. Other excitation methods, such as step relaxation and transient random, lead to signal-processing requirements similar to those of impact data. However, such methods are outside the scope of this document because they involve the use of an exciter which is attached to the structure.

The signal analysis methods covered are all based on the discrete Fourier transform (DFT), which is performed mostly by a fast Fourier transform (FFT) algorithm. This restriction in scope is based solely on the wide availability of equipment which implements these methods and on the large base of experience in using these methods. It is not intended to exclude the use of other methods currently under development.

Impact excitation is also widely used to obtain uncalibrated frequency-response information. For example, a quick impact test which obtains approximate natural frequencies and mode shapes can be quite helpful in planning a random or sinusoidal test for accurate mobility measurements. These uses of impact excitation to obtain qualitative results can be a first stage for mobility measurements.

This document is limited to the use of impact excitation techniques for making accurate mobility measurements.

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.

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and the following apply.

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
frequency-response function
FRF
frequency-dependent ratio of Fourier transform of the motion-response of a linear system to the one of the excitation force

Note 1 to entry: Frequency-response functions are properties of linear dynamic systems which do not depend on the type of excitation function. Excitation may be harmonic, random or transient functions of time. The test results obtained with one type of excitation may thus be used for predicting the response of the linear system to any other type of excitation.

Note 2 to entry: Linearity of the system is a condition which, in practice, may be met only approximately, depending on the type of system and on the magnitude of the input. Care has to be taken to avoid nonlinear effects, particularly when applying impulse excitation. Structures which are known to be nonlinear (for example, certain riveted structures) should not be tested with impulse excitation and great care is required when using random excitation for testing such structures.

Note 3 to entry: Motion may be expressed in terms of either displacement, velocity or acceleration; the corresponding frequency-response function designations are dynamic compliance, mobility and accelerance or dynamic stiffness, impedance, and effective mass, respectively.

Note 4 to entry: In practice, the discrete Fourier transform (DFT) by the fast Fourier transform (FFT) is used as an approximation of the continuous Fourier transform. The errors of this approximation can be reduced to levels below those of other measurement errors. Hence, the use of the DFT does not necessarily limit the accuracy of the measurement.

3.2
frequency range of interest
span, in hertz, from the lowest frequency to the highest frequency at which mobility data are to be obtained in a given test series

3.3
power spectral density
square of absolute value of the FFT of a signal multiplied by $2/T$ where T is the length of the time signal, meaning mean-square value of a time signal per unit bandwidth

3.4
energy spectral density
power spectral density (3.3) multiplied by the length of the record in seconds, which is used in the spectral calculation of a transient signal

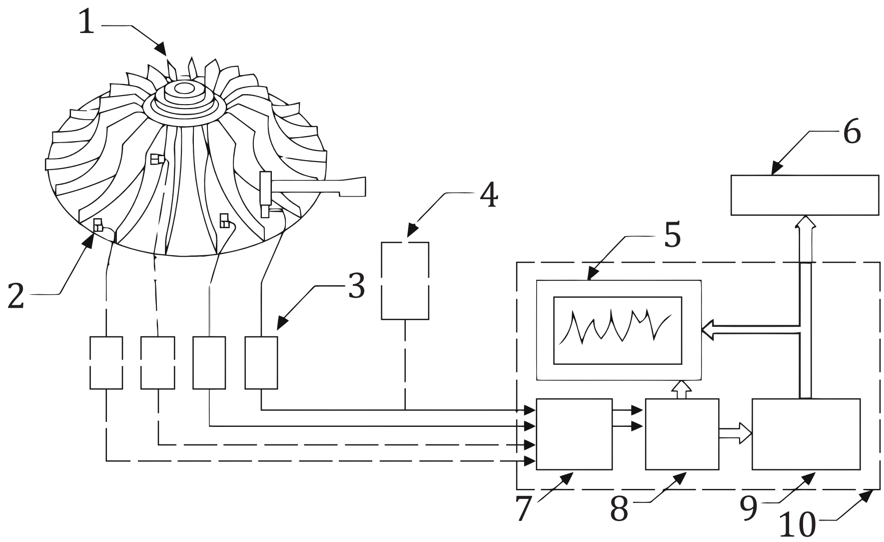
Note 1 to entry: This definition assumes that the transient signal is entirely contained within the record.

4 General characteristics of impact measurements

4.1 General description

The instrumentation required for mobility measurements using impact excitation consists of an impact hammer with built-in force transducer, one or more motion-response transducers with their associated signal conditioners and a digital Fourier transform analysis system or analyser having at least two simultaneous input channels. The instrumentation system is shown schematically in Figure 1. This document provides information on the selection and use of these components.

The force and response signals from each impact are anti-aliasing filtered and then digitally sampled using the pre-triggering or transient capture mode of the analyser. Each of the resulting digital records should represent a single impact event. The discrete Fourier transform of each record is computed by the analyser. Frequency domain averaging of several frequency-response functions obtained from impacts at a given point may be performed to improve the estimate.



Key

1 structure under test
2 motion-response transducer(s)
3 signal conditioners
4 storage oscilloscope
5 display
6 output device (printer/plotter)
7 amplifiers and analogue anti-aliasing filter
8 analogue/digital converter
9 DFT/FFT and FRF computation
10 signal analyser

________ basic feature
-------- optional feature
DFT discrete Fourier transform
FFT fast Fourier transform
FRF frequency response function

Figure 1 — Instrumentation block diagram for impact excitation

4.2 Advantages and limitations of impact excitation

4.2.1 General

Impact excitation offers the following intrinsic advantages compared with the use of an attached exciter:

a) measurement speed;

b) ease of installation;

c) ease of relocating the excitation point;

d) no change of structure, which can be caused by the exciter attachment method (see ISO 7626-2).

On the other hand, the following limitations of impact excitation shall be taken into account:

a) nonlinearity restrictions;

b) signal-to-noise problems;

c) limited frequency resolution;

d) damping restrictions;

e) dependence on operator skill.

These limitations are discussed in 4.2.2 to 4.2.6.

4.2.2 Nonlinearity restrictions

Mobility measurements on structures which exhibit a significant degree of nonlinearity always demand special precautions. In such cases, the use of sinusoidal or random excitation with an attached exciter is preferred, if practical, instead of the impact-excitation technique.

With the impact-excitation technique, the energy needed to drive the response signal to a certain magnitude is put into the structure during a limited part of the time period used for analysis. Compared with sinusoidal or random excitation, the force of the impact pulse therefore can be much larger and the effects of nonlinearity are thus likely to be increased.

For measurements on systems with a significant degree of nonlinearity, it is very important to keep a level of the force used for the excitation or a level of the system response. In this aspect, the sinusoidal excitation techniques are preferable. If a hand-held hammer is used to generate the impacts, the individual force amplitudes can vary significantly. The repeatability of such a measurement can be poor for nonlinear systems.

4.2.3 Signal-to-noise problems

Because the average signal levels are low compared with the peak levels, impact measurements require a very low noise testing environment and the maximum possible dynamic range in the measurement system. This requirement can rule out the use of current analogue tape-recording techniques.

A significant noise problem can occur because the force signal duration is short compared with the total record length. This situation can result in the instrumentation electrical noise and the mechanically induced background noise having a mean square value that is significant compared with the mean square value of the input force. Such noise can be reduced by the windowing techniques described in 8.5.

4.2.4 Limited frequency resolution

The frequency increment, in hertz, which results from a discrete Fourier transform (including the case of a band-limited or “zoom” analysis), is equal to the reciprocal of the record length, in seconds. Because each record represents a single impact event, the record length is effectively limited to the time required for the impulse response of the structure to decay to the level of the background noise. Therefore, the frequency resolution attainable depends on both the response of the structure and the background noise level. In some cases, it can be impractical (and unnecessary) using impact excitation to achieve directly the frequency resolution specified in ISO 7626-2; however, accurate mobility values can be obtained at discrete frequencies with sufficiently fine resolution for most applications. If the test structure exhibits high modal density (i.e. multiple resonances within a narrow frequency band), it can be difficult to achieve sufficiently fine resolution for an accurate mobility measurement. In those cases, one of the steady-state excitation methods with “zoom” analysis is preferred.

By its very nature, the spectrum of an impact extends from DC to some upper frequency limit (see Clause 6). This inability to band limit the excitation spectrum restricts the usefulness of “zoom” analysis for improving the frequency resolution of impact measurements, and the impact places further demands on the dynamic range of the measurement system. It also increases the danger of undetected overloads (clipping) in the measurement system due to high-amplitude out-of-band signals. See 6.3 and 8.4. The time resolution has to be high enough for the impact signal to be recorded at a sufficient number of sampling points. However, a higher time resolution can decrease the frequency resolution when the number of data points for the FFT is fixed.

4.2.5 Damping restrictions

Impact excitation has limitations for testing heavily damped structures because the short duration of the response signal leads to a trade-off between frequency resolution and background noise level, as discussed in 4.2.4. This limitation can also be understood as a manifestation of the inherently low average energy level for a given impact force magnitude. Heavily damped structures can require higher energy excitation in order to balance their high internal energy dissipation characteristics and to produce sufficient response data for accurate measurement.

A different problem occurs if the structure has extremely light damping. The frequency-response functions of such a structure exhibit very sharp resonance peaks which requires high-resolution zoom measurements for accurate definition, as discussed in 4.2.4. The use of an exponential decay window can help by adding a known amount of artificial decay to the data. If windowing is used, the resulting mobility data or modal damping values therefrom have to be corrected, as described in 8.5 and Annex A.

4.2.6 Dependence on operator skill

The accuracy of mobility measurements performed using a hand-held impact hammer depends on the ability of the operator to maintain the correct location and direction of impact. These effects can normally be held within acceptable limits if the impacts are applied carefully, but they can be significant if the test structure is small and requires very fine spatial resolution.

Operator skill is also required in order to avoid a double hit of impactor; see 6.4. If there are high demands on the quality, the shock may be applied by a mechanical pendulum to avoid double hits.

5 Support of the structure under test

5.1 General

Mobility measurements may be performed on structures either in an ungrounded condition (freely suspended) or in a grounded condition (attached to one or more supports), depending on the objective of the test.

5.2 Ungrounded measurements

Ungrounded measurements employ a compliant suspension of the test structure. The magnitudes of the driving-point mobility of the suspension at points of attachments should be at least ten times greater than the magnitudes of the mobility of the structure at the same attachment points.

5.3 Grounded measurements

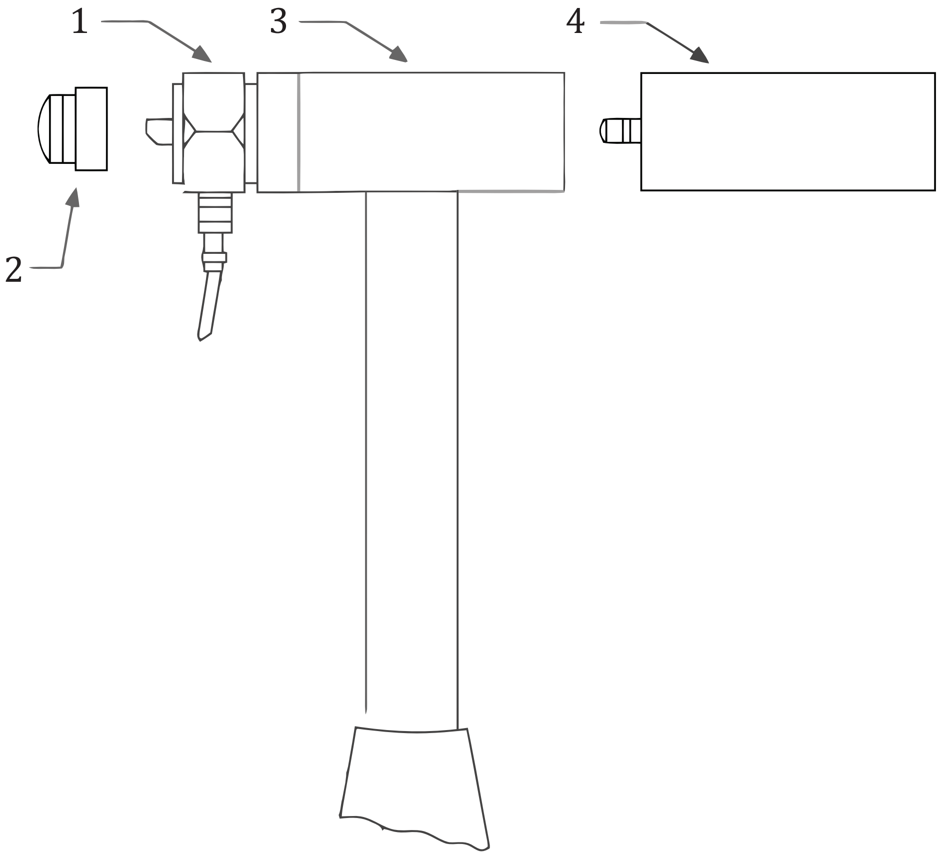
Grounded measurements employ a support of the test structure which is representative of its support in typical applications, unless otherwise specified. A description of the support and attachment should be included in the test report.

FRFs and modal parameters resulting from grounded measurements can differ significantly from those measured in ungrounded (free-free) configuration. Due to the clamping, the structure is stiffened in general and, hence, the natural frequencies increase.

6 Application of the excitation

6.1 Impactor design

A typical impactor consists of a rigid mass with a force transducer attached to one end and an impact tip attached to the opposite side of the force transducer, as shown schematically in Figure 2. The tip stiffness and impactor mass shall be selected as described in 6.3, in order to achieve a force pulse of the desired duration and to avoid double hits.



Key

1 force transducer

2 interchangeable impactor tip

3 mass

4 interchangeable mass

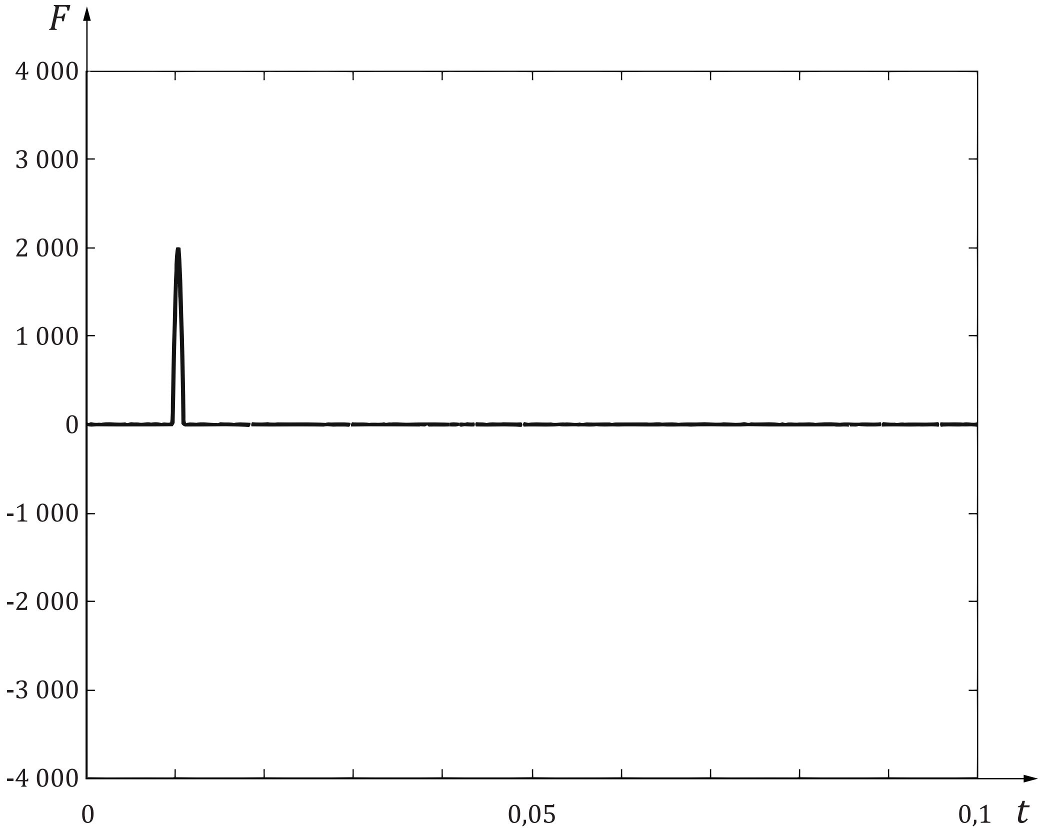
Figure 2 — Typical impactor

For small values of impactor mass, the impactor often takes the form of a hand-held hammer with interchangeable tips and masses. However, the accuracy obtained using a hand-held impactor depends on the skill of the operator in maintaining the correct location and direction of impact. For small test structures, it is necessary to provide a suitable mechanical device to guide the impactor to a repeatable location and direction on the structure. For testing large structures which require higher energy, the impactor may take the form of a large mass suspended from cables and either dropped or swung. Alternatively, a smaller mass may be accelerated to a high impact velocity by a spring, solenoid pneumatic actuator or other means.

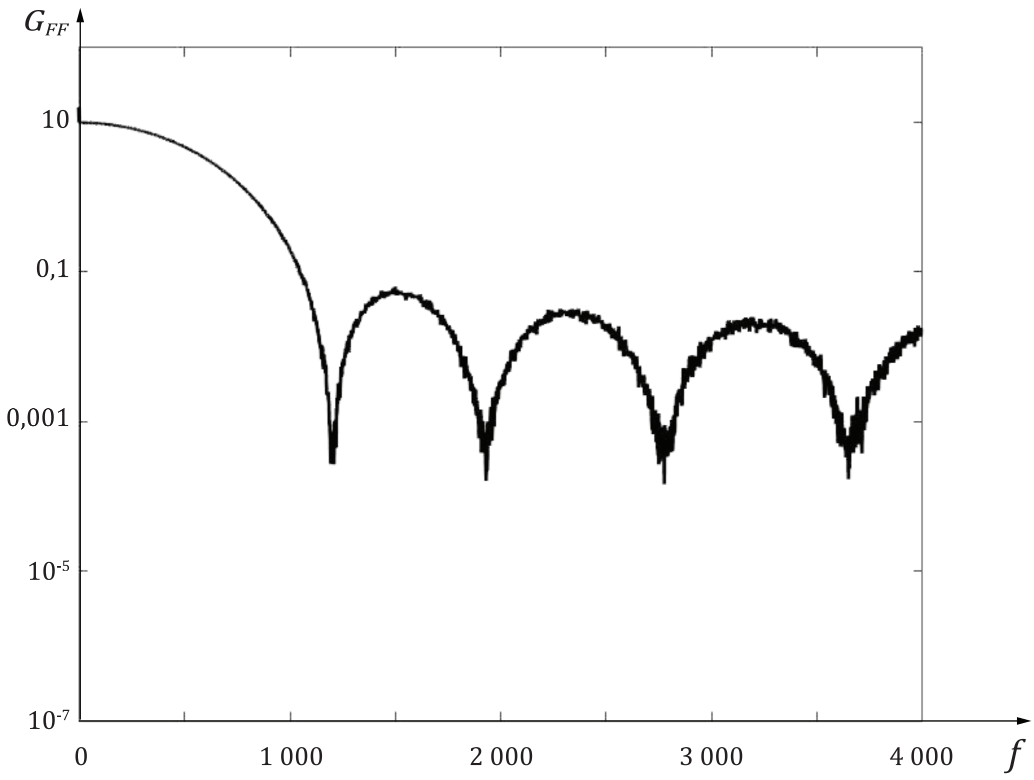
The area of the impact surface of the tip should be large enough to withstand the maximum force employed without permanent deformation of either the tip or the test structure. On the other hand, a small tip area is necessary if very fine spatial resolution of the location is required. The velocity vector of the impactor at the moment of impact should be in line with the sensing axis of the force transducer and should be perpendicular to the surface of the test structure at the point of impact within 10°. It is generally easier to maintain the proper orientation if the impactor body is relatively long compared with its cross-sectional dimensions.

6.2 Force spectrum characteristics

A theoretical (Dirac) impulse of infinitesimal duration contains equal energy at all frequencies. However, the spectrum of any actual force pulse has a finite usable bandwidth which is inversely proportional to the duration of the pulse. This provides a useful means of concentrating the main excitation energy into the frequency range below the maximum frequency of interest. In practice, the spectrum of a single force pulse typically has the form of a main lobe at low frequency followed by higher-frequency side-lobes whose magnitudes decrease rapidly with frequency. Figure 3 shows a force pulse and the corresponding energy spectral density. The usable frequency range of this pulse extends up to about 1 000 Hz, depending on the response characteristics of the structure under test.



a) Time history of impact force, unfiltered



b) Energy spectral density corresponding to Figure 3 a)

Key

F force, N

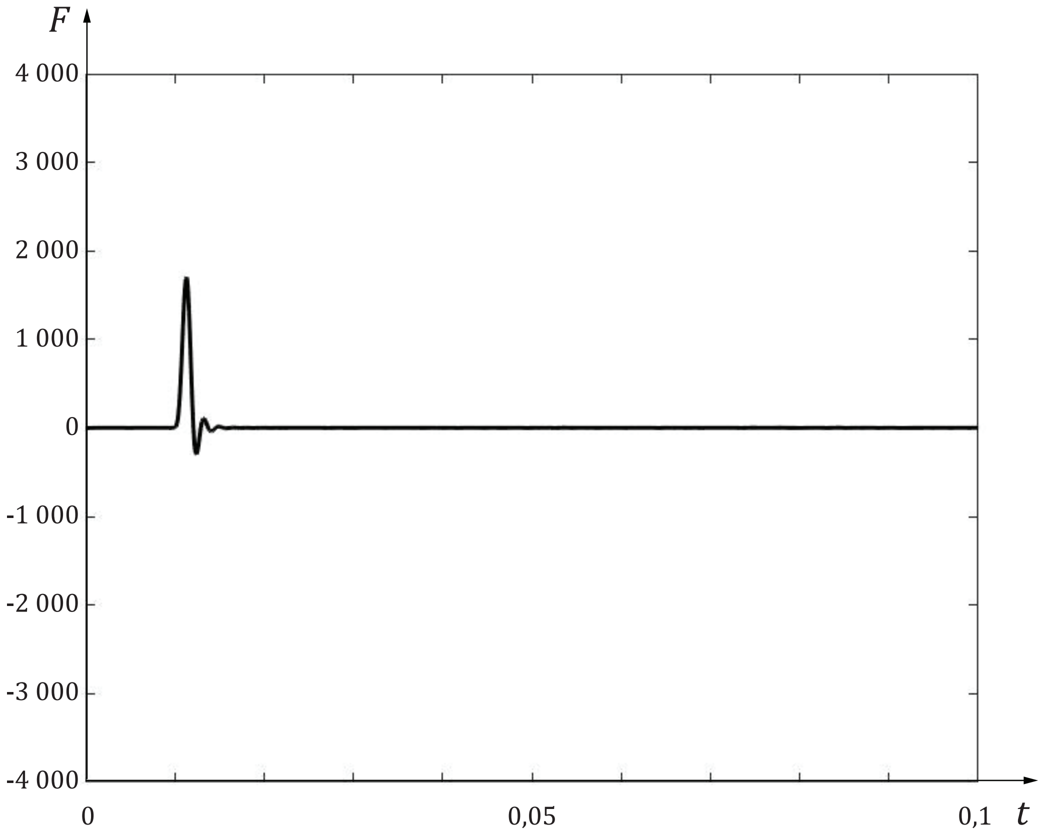
t time, s

G_{FF} force energy spectral density, N^2s/Hz

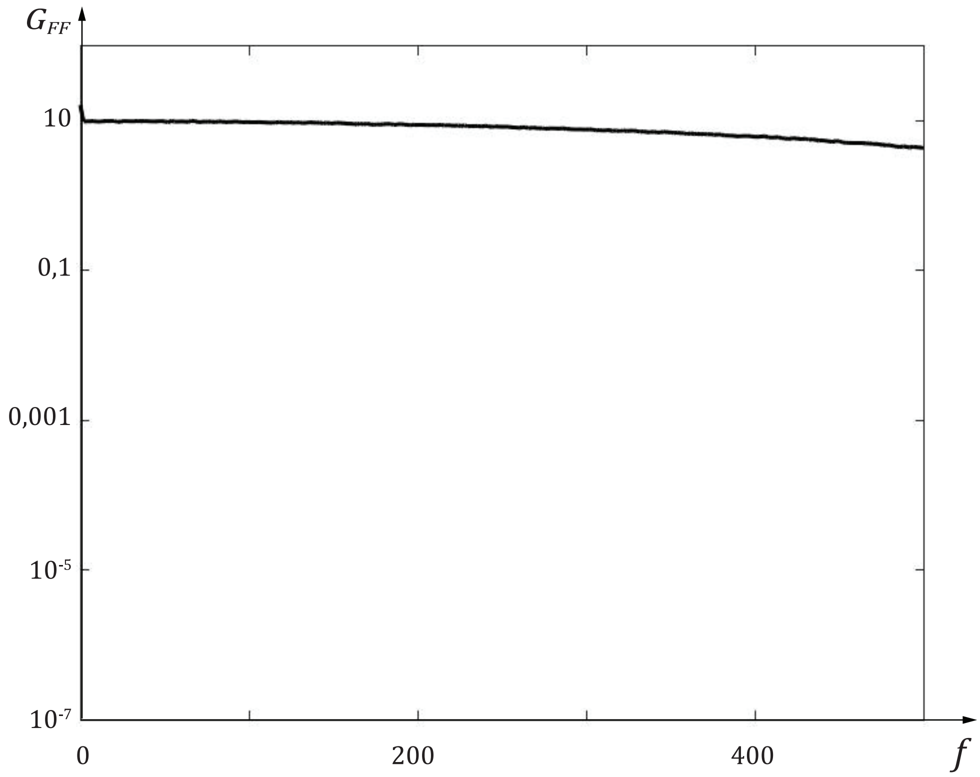
f frequency, Hz

Figure 3 — Typical force pulse and spectrum

There is an inherent trade-off between time-domain resolution and frequency-domain resolution in the discrete Fourier transform. Due to the sampling relationships of the discrete Fourier transform (see 8.3), the force waveform is represented by only a few discrete samples in the digital record used by the Fourier analyser. The force waveform is also shaped by the anti-aliasing filter. These factors, which are necessary for accurate frequency-domain analysis, make the digital records ill-suited for monitoring the force waveform in time domain during impact measurements (unless the analysis bandwidth is increased to a frequency well above the usable frequency range of the force pulse). Figure 4 shows the same force pulse as Figure 3, but low-pass filtered at 625 Hz by the analogue anti-aliasing filter. The two energy densities show good agreement, although the digitized force waveform in Figure 4 shows a considerably different shape and peak magnitude.



a) Time history of impact force, low-pass filtered at 625 Hz



b) Energy spectral density corresponding to Figure 4 a)

Key

F force, N

t time, s

G_{FF} force energy spectral density, N^2s/Hz

f frequency, Hz

Figure 4 — Effects of low-pass filtering on the force pulse of Figure 3 a) and its spectrum

6.3 Control of the frequency range of excitation

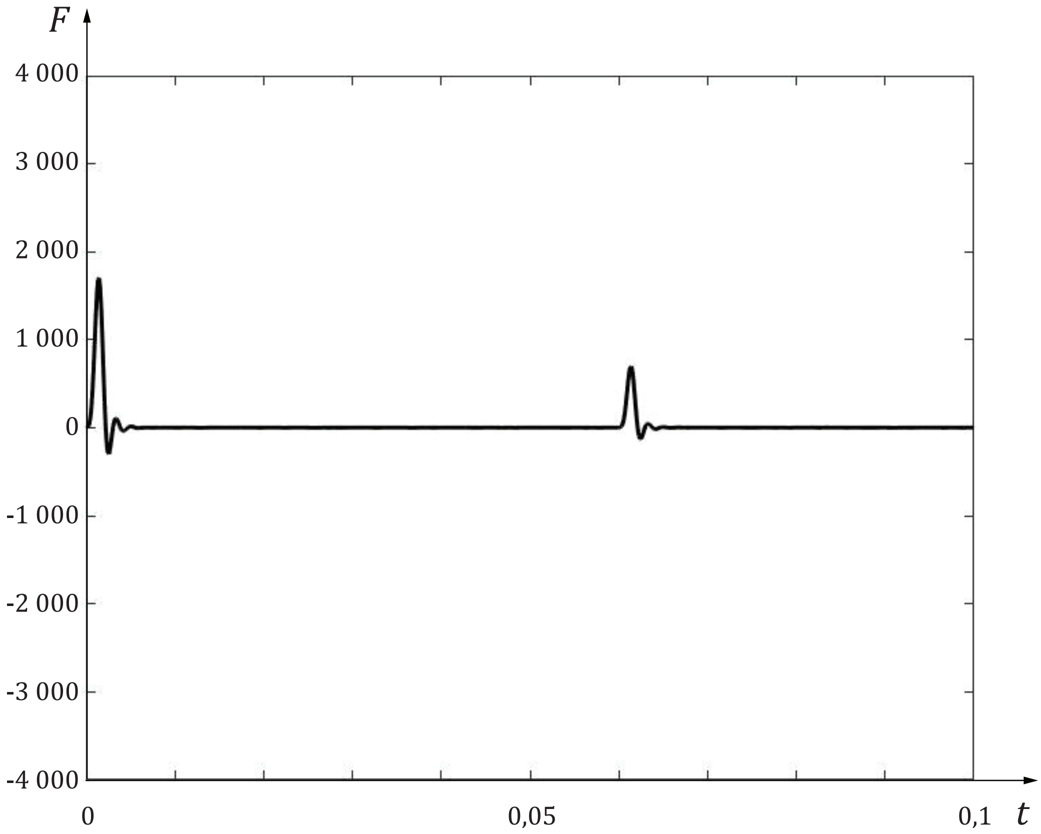
In order to make optimum use of the dynamic range of the measurement system, it is desirable to limit the frequency range of excitation to the maximum frequency of interest. The excitation bandwidth is controlled by the tip stiffness and the impactor mass. The frequency range of a given impactor can be reduced either by decreasing the tip stiffness or by increasing the impactor mass.

The actual frequency range achieved also depends on the effective stiffness and mass of the test structure at the point of impact. Low structure stiffness sometimes limits the increase in frequency range achievable by increasing the tip stiffness. In this case, a more effective method of increasing the frequency range of the excitation is to reduce the mass of the impactor.

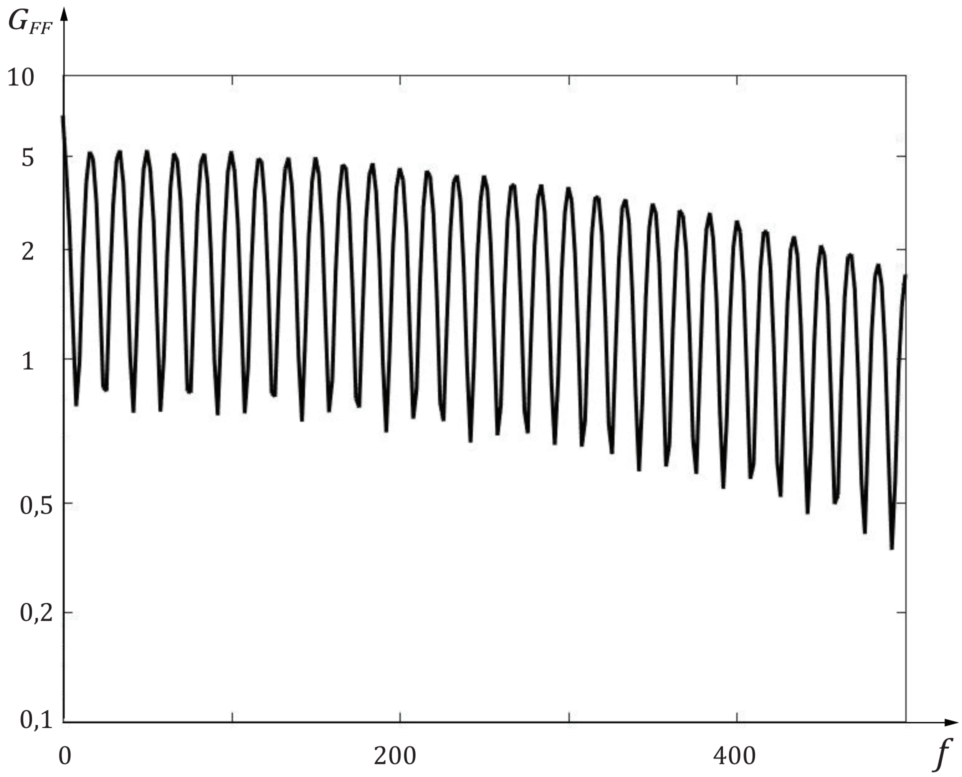
The force and response spectra should be checked for excessive energy above the frequency range of interest by using a force whose actual frequency range becomes equal to the maximum likely to be employed during the test. The impactor characteristics should then be adjusted, if necessary, to achieve the desired frequency range.

6.4 Avoidance of impactor double hits

If more than a single impact occurs within the data record, the Fourier transforms of the pulses tend to cancel at certain frequencies, creating sharp notches in the force spectrum (see Figure 5). This can cause significant errors in the mobility measurement at these frequencies, due to a low signal-to-noise ratio in the force spectrum. Even if the impact is applied very carefully, it can be impossible to avoid double hits when exciting at a very responsive point on the test structure with a relatively massive impactor. The solution is to reduce the mass of the impactor; the tip stiffness should then be adjusted to maintain the desired frequency range of excitation.



a) Time history of double-impact force



b) Energy spectral density corresponding to Figure 5 a)

Key

F force, N

t time, s

G_{FF} force energy spectral density, N^2s/Hz

f frequency, Hz

Figure 5 — Spectrum effects of double impacts in the force record

If the second impact is small compared with the primary impact, the force spectrum can exhibit a slight ripple rather than deep notches. Moderate dips in the force spectrum may normally be tolerated. Multiple impacts are most easily detected in the frequency domain by checking the force spectrum at each impact location. It is also desirable to monitor the time-domain waveform; a storage-type oscilloscope may be used to observe the unfiltered force signal, so that the anti-aliasing filter does not obscure secondary impacts "ringing" from the primary impact.

Never use a "force window" (see 8.5) to eliminate secondary impacts from the force record prior to Fourier processing. When using a force window to reduce noise in the force signal, make sure that it does not mask multiple impacts which actually occur. The response still includes the effects of the multiple impacts, thus resulting in an erroneous estimate of the frequency response function.

7 Transducer system

7.1 General

Transducers and their associated signal conditioning should be selected in accordance with the criteria given in ISO 7626-1 and ISO 7626-2. For use in impact measurements, it is especially important that the transducer system has low noise and a large linear dynamic range.

7.2 Impactor calibration

Although the effective mass between the force transducer and the structure under test does not affect the motion-response signal, it can have a significant effect on the force calibration of the impactor. The following operational calibration test should be performed at the beginning and end of each series of measurements, and it should be repeated whenever the mass or tip of the impactor is changed.

This operational calibration is essentially the same as the procedure described in ISO 7626-2:2015, 7.5.2; it is performed by measuring either the mobility or the accelerance of a freely suspended rigid calibration block of known mass. The measured frequency response for the calibration block should agree with its known value (for example, an accelerance magnitude of $1/m$, where m is the total mass of the calibration block, including any attached transducers) within ±5 % over the frequency range of interest. This should be accomplished by using a known calibration value for the motion-response transducer and adjusting the calibration constant for the signal to achieve the correct mobility or accelerance magnitude. The operational calibration test should also be performed on any additional response transducers which are used in the measurements (for example multi-axis response transducers); these transducers should be assigned calibration values consistent with the force calibration obtained above. The measurement system and the impactor shall be in the same configuration as used in the mobility measurements which employ this calibration value. The mass of the calibration block shall be chosen so that its mobility is representative of the range of mobilities to be measured.

If the calibration measurement does not yield an accelerance value which is essentially constant over the frequency range of interest, the cause of this discrepancy should be investigated and resolved before proceeding with the test.

8 Processing of the transducer signals

8.1 Filtering

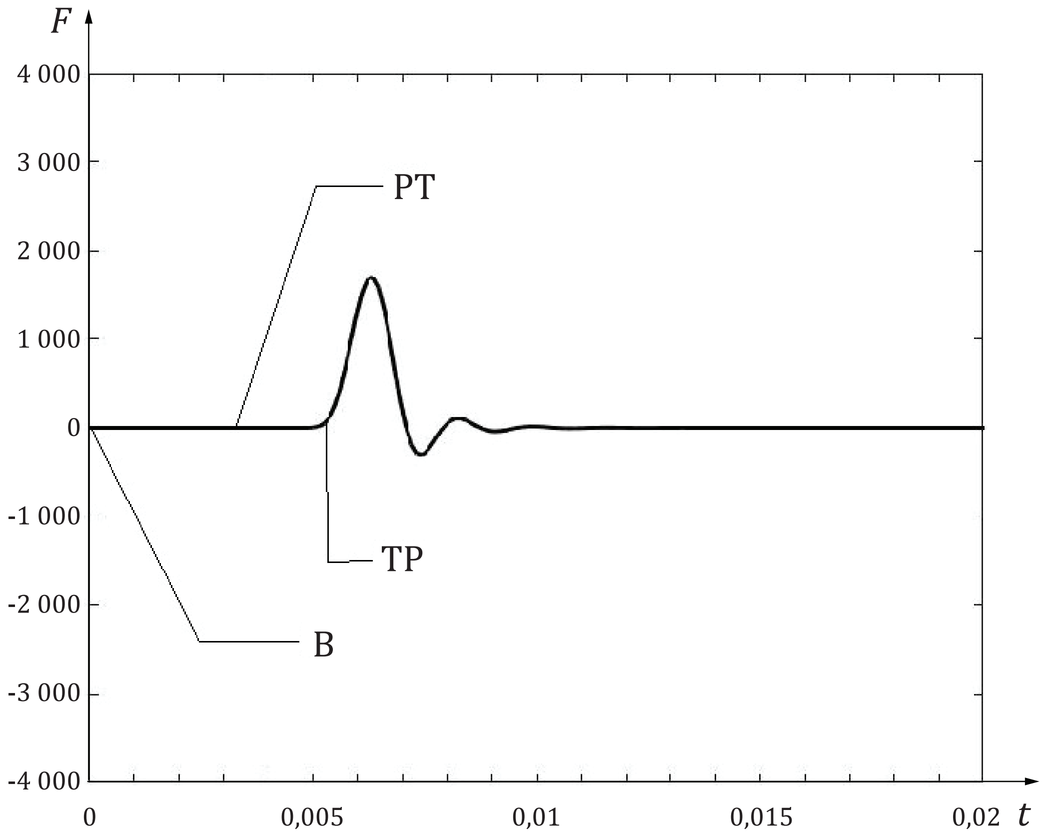
The transducer signals shall be low-pass filtered in an analogue way before the data are sampled and digitized by the Fourier analyser, in order to prevent out-of-band signals from being improperly interpreted within the analysis range, a phenomenon known as "aliasing". Most commercially available analysers include built-in filters with cut-off frequencies matched to the available frequency ranges of the analyser. The adequacy of alias protection can be checked by using a good-quality signal generator to produce a full-scale sine wave input at a variety of out-of-band frequencies and checking the resulting spectra for spurious in-band frequency components. The most important frequencies to be used for the adequacy checking are between the maximum analysis frequency and the sampling frequency. Thus, the measured spectrum should not show any amplitudes resulting from frequency components whose frequencies are between the maximum analysis frequency and the sampling frequency.

Other important filter characteristics include the channel-to-channel gain and phase match within the pass-band. The operational calibration test given in ISO 7626-2:2015, 7.5.2 includes these factors, along with all other aspects of the measurement system. The channel-to-channel match of the filters and analyser can be checked by connecting the same broad-band (random or impulsive) signal to all filter channels and measuring the frequency response between each pair of channels. The magnitude of the frequency response should equal unity within ±5 % over the frequency range of interest, and the phase should be zero within ±5°.

In order to make full use of the dynamic range of the analyser, it can be desirable to employ a high-pass filter to attenuate signal components below the frequency range of interest. In particular, any DC component in the transducer signals can be eliminated by "AC coupling" the inputs to the analyser. This is especially important if windowing is employed (see 8.5). If high-pass filtering is used, make sure that it does not introduce gain or phase errors within the frequency range of interest.

8.2 Transient capture characteristics

The digital record of each impact should be acquired using the pre-triggering mode of the analyser, in order to place the beginning of the impact near the start of the digital record. The digital record should include a small amount of pre-trigger data in order to ensure that the leading edge of the impact is not lost. See Figure 6. If the analyser lacks pre-trigger capability, the best method is to use external triggering on the unfiltered force signal.



Key

PT pre-trigger data

TP triggering point

B beginning of record

Figure 6 — Time history of transient force captured with pre-trigger

8.3 Sampling relationships

Each digital record for Fourier processing consists of a fixed number, N, of equally spaced discrete samples from a filtered analogue waveform. The block size N of the discrete Fourier transform (DFT) is usually a power of two, because efficient FFT algorithms exist for such values. A block size of 1 024, 2 048 or 4 096 samples is typical in current designs. The record length is $T = N\Delta t$, where Δt is the sampling interval, in seconds. The sampling frequency is $1/\Delta t$.

The DFT of such a record produces $(N/2) + 1$ non-redundant complex Fourier coefficients which represent the spectrum at discrete frequencies with a spacing of $\Delta f = 1/T$ Hz from 0 Hz up to half the sampling frequency (known as the Nyquist frequency). In practice, the cut-off frequency of the filters shall be set to a value somewhat below the Nyquist frequency in order to prevent aliasing, because the filters are not infinitely sharp. Typically, the sampling frequency is from 2,56 to 4 times the filter cut-off frequency, depending on the filter roll-off characteristics; for a block size of 1 024, this yields between 400 and 256 “spectral lines” of valid frequency domain information from the DFT.

For the case of transient data which are entirely contained within the digital record, the DFT coincides with the true Fourier transform over the frequency range measured; that is, the discrete spectral values of the DFT are samples from the idealized continuous spectrum. The response signals from an impact test on a linear structure take the form of a summation of exponentially decaying sinusoids, plus some background noise. The best results are usually obtained if the response signal decays to about 1 % of its initial magnitude at the end of the record. This figure represents a compromise: using a longer record to capture the response down to the limit of detection can improve the frequency resolution but it can decrease the signal-to-noise ratio of the measurement; using a shorter record leads to excessive truncation of the response and causes the signal processing error known as "leakage" to become significant.

Since the record length T is the product of the block size N and the sampling interval Δt, it can seem that the record length can be controlled by proper manipulation of these two factors. However, the sampling frequency is fixed by the desired frequency range, and the block size is constrained by the design of the Fourier analyser employed. In particular, very lightly damped structures can require an extremely large block size if this approach is taken. Two additional methods are more commonly used to deal with this case.

a) An exponential window (see 8.5) may be used to add a known amount of artificial decay to the data before Fourier processing.

b) Zoom processing may be employed to increase the effective record length without actually increasing the block size. Zoom provides enhanced frequency resolution within a reduced analysis band.

8.4 Avoidance of saturation (clipping)

Impact excitation presents a particular risk of saturating the measurement system, due to the likelihood of significant amounts of out-of-band energy in the signals. Furthermore, the need to use the maximum dynamic range available means that the peak signal values can often be rather close to the saturation limits at various points in the measurement system. As noted in 6.2, the digital records, which are filtered, sometimes provide poor definition of the actual waveforms; they should not be relied on for the detection of saturation. The best means of avoiding saturation is to monitor the unfiltered signals with a storage-type oscilloscope having a bandwidth which extends well beyond the signal bandwidth. If this is not available, the signals should be checked using the Fourier analyser on a frequency range well above the highest frequency present in the data; this check should be performed at each location prior to the mobility measurement, using an impact force equal to the highest which is used during the measurement.

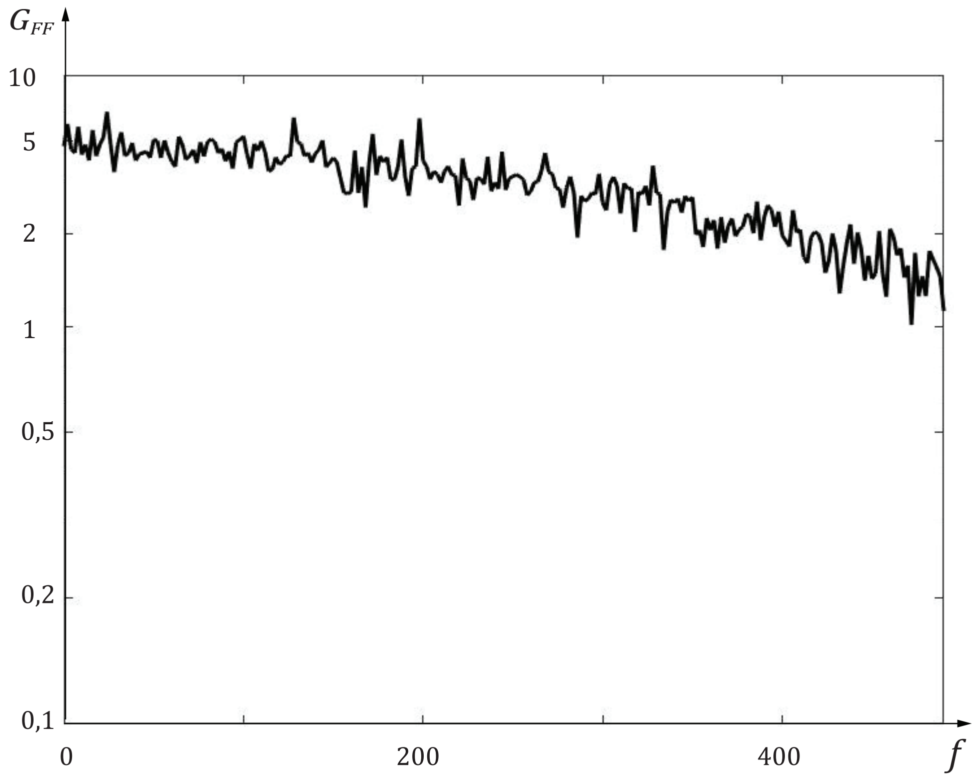
Saturation problems are not always evident as a clipped appearance in the transducer waveforms; the manufacturer's specifications for the maximum voltage for linear operation should be observed. Saturation can be eliminated by reducing the impact force, reducing the gain in the signal conditioner and/or the Fourier analyser, or by selecting a less sensitive transducer, as appropriate.

8.5 Windowing techniques

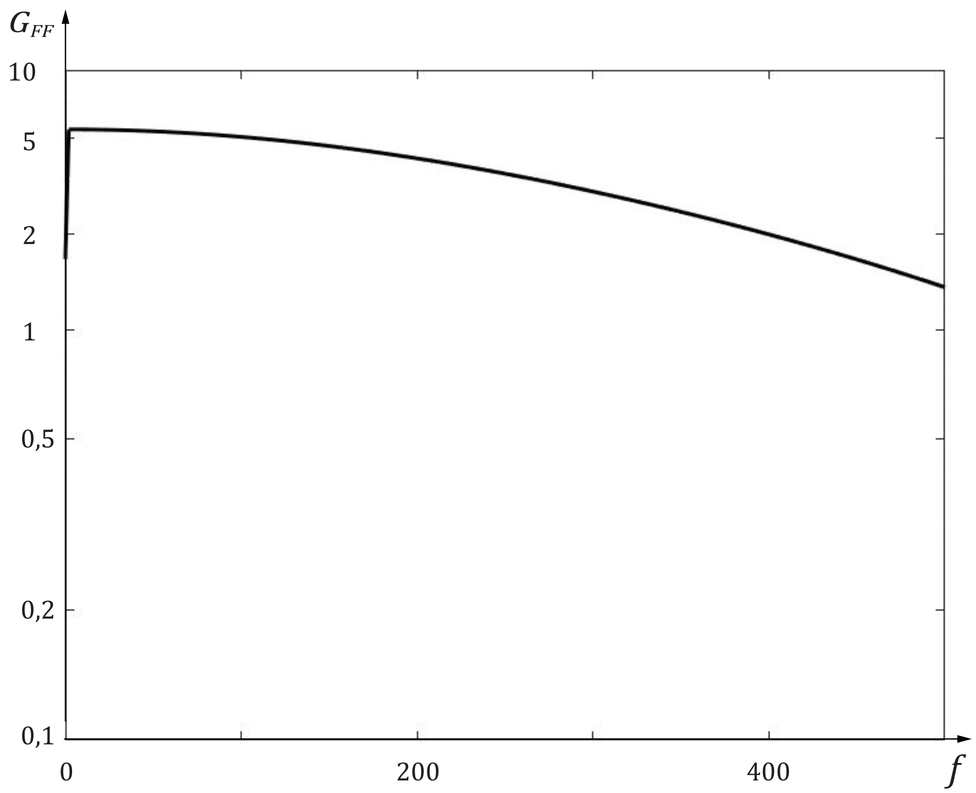
8.5.1 Force signal

Because the impact force signal represents a very small portion of the digital record analysed (typically less than 1 %), even very low level noise can produce significant errors in the auto-spectrum of the force. This is especially true if either zoom or a very large block size is used. Such noise is not reduced by averaging with the usual frequency-response function estimate, since the noise is additive in the force auto-spectrum[7].

Random noise can be greatly reduced by multiplying the force record by a "force window" [see Figure 8 c)] which has unity gain for a portion of the record which includes the force signal (including the filter response), and sets the remaining samples in the record to a value of exactly zero prior to Fourier processing. This procedure introduces no distortion as long as none of the force data is attenuated and the background noise is broad-band in nature. Figure 7 compares the energy spectral density of a typical pulse with and without force windowing.



a) Energy spectral density of force without force window



b) Energy spectral density of force with force window

Key

G_{FF} force energy spectral density, N^2s/Hz

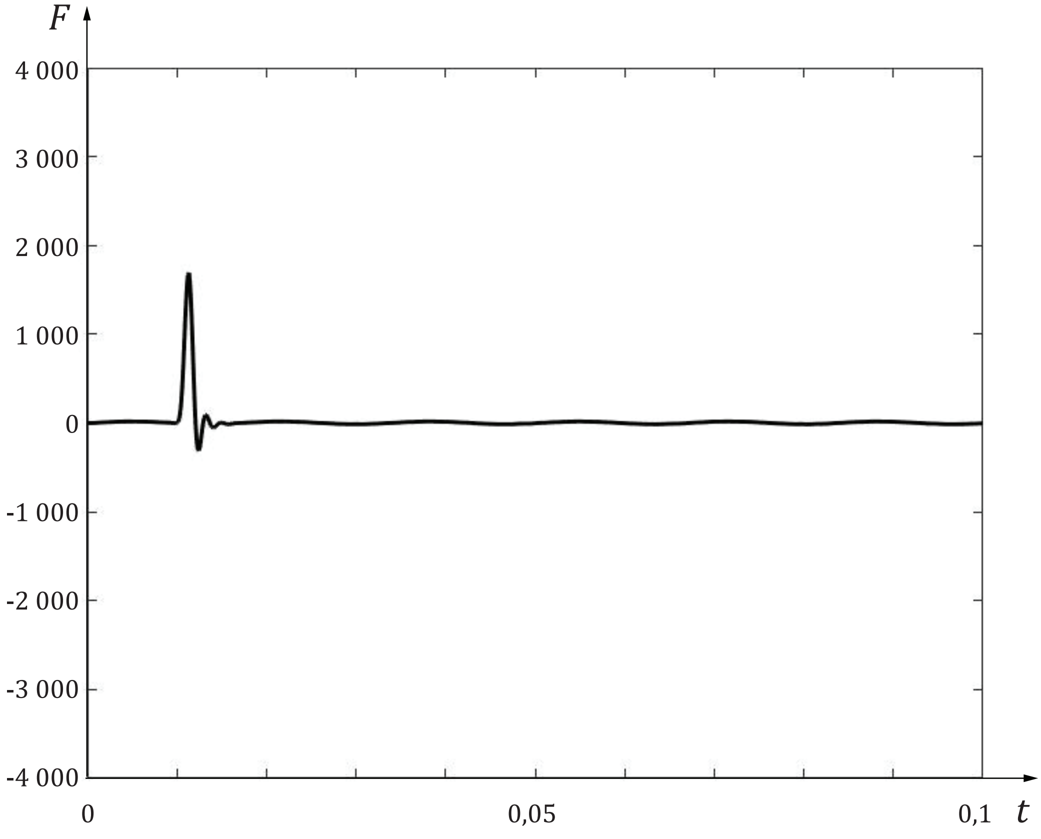
f frequency, Hz

Figure 7 — Effect of "force windowing"

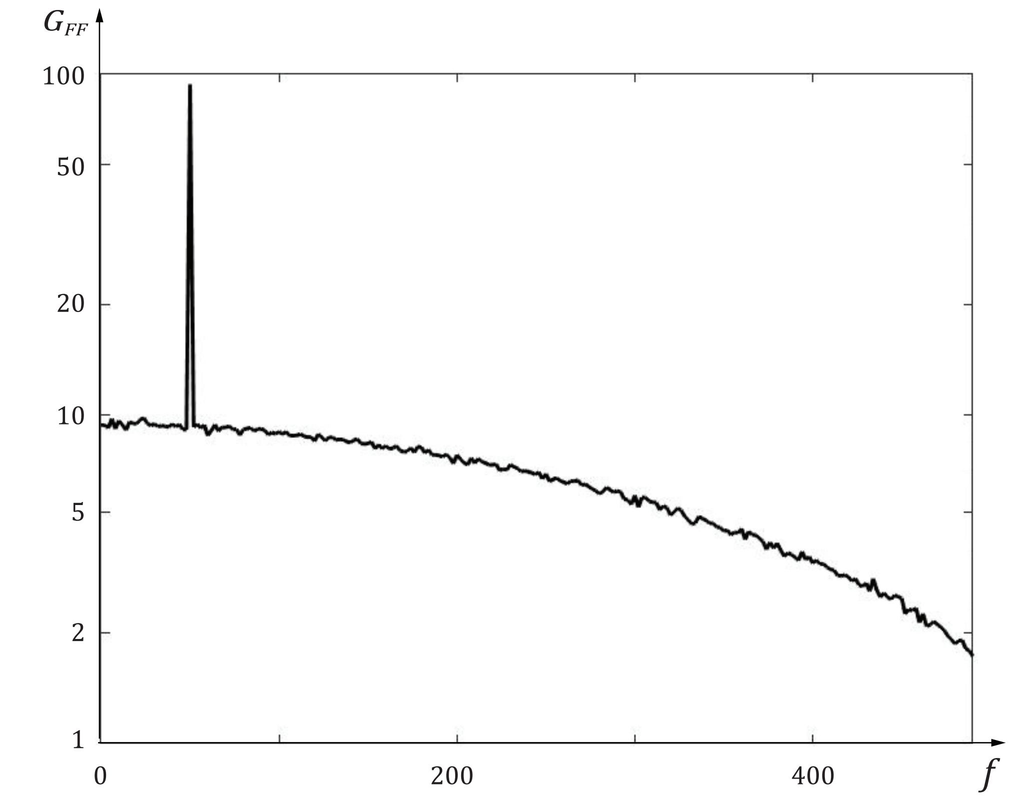
If the force record contains significant levels of periodic noise or DC offset, then force windowing can reduce its magnitude in the spectrum; however, the spectrum of the noise spreads over a rather wide frequency range due to FFT leakage caused by truncation of the continuous noise signal. Therefore, noise which occurs at discrete frequencies of no interest (such as 0 Hz or power line frequency) can contaminate a significant portion of the frequency range of interest after windowing. Leakage can be restricted to a somewhat narrower frequency band by using a force window which makes a smooth transition between zero and one, as described in Reference [6]. However, the best approach is to eliminate all periodic and DC noise components from the data before applying a force window.

Figure 8 shows the effect of windowing a force signal with excessive 60 Hz noise using a rectangular force window.

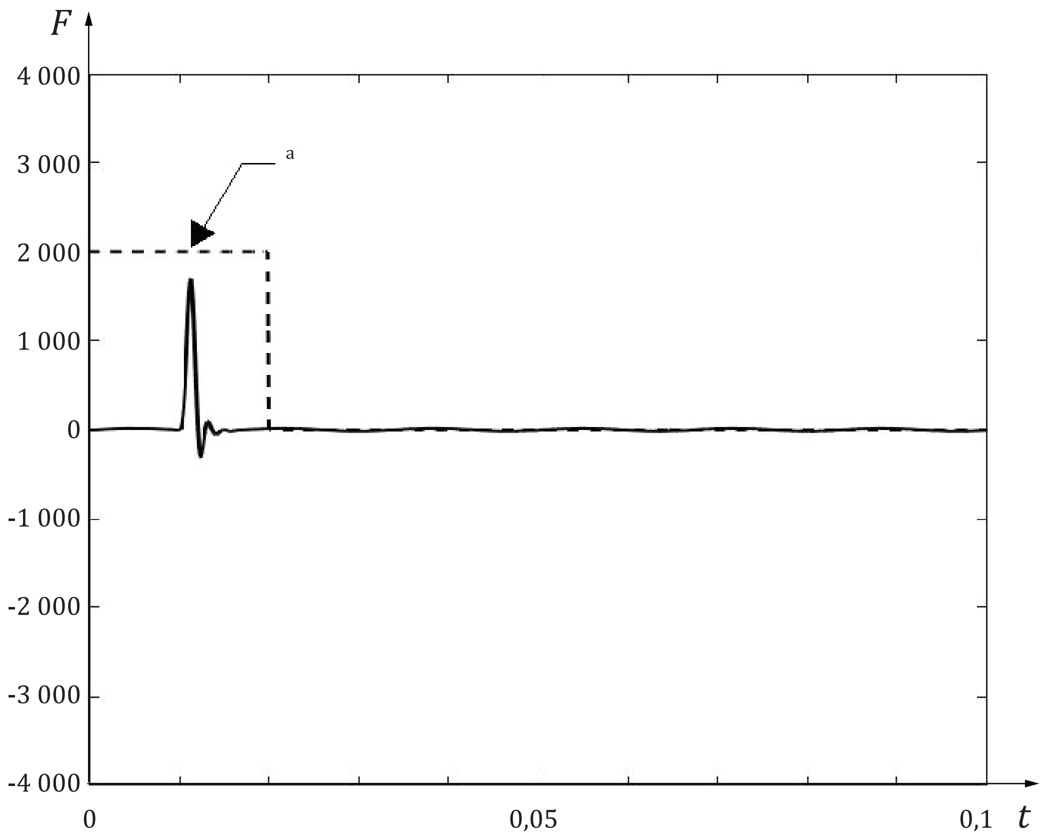
NOTE The same warning applies to the use of the exponential window described in 8.5.2.



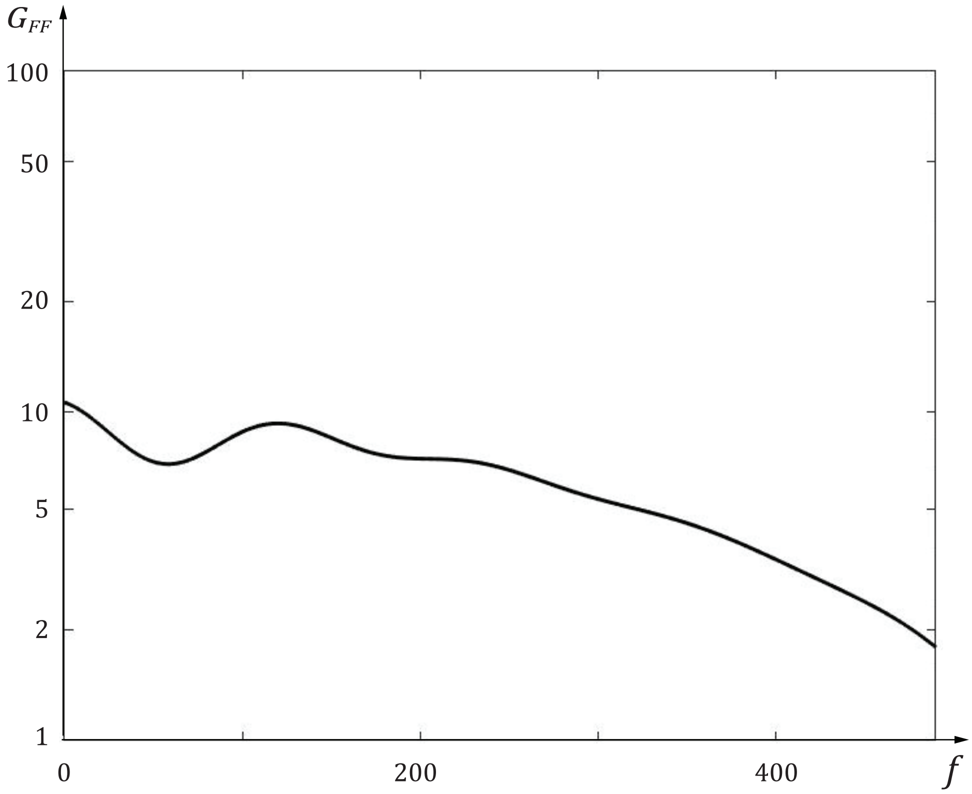
a) Time history of force with low periodic noise



b) Energy spectral density corresponding to Figure 8 a)



c) Time history of force with rectangular force window



d) Energy spectral density corresponding to Figure 8 c)

Key

F force, N

t time, s

G_{FF} force energy spectral density, N^2s/Hz

f frequency, Hz

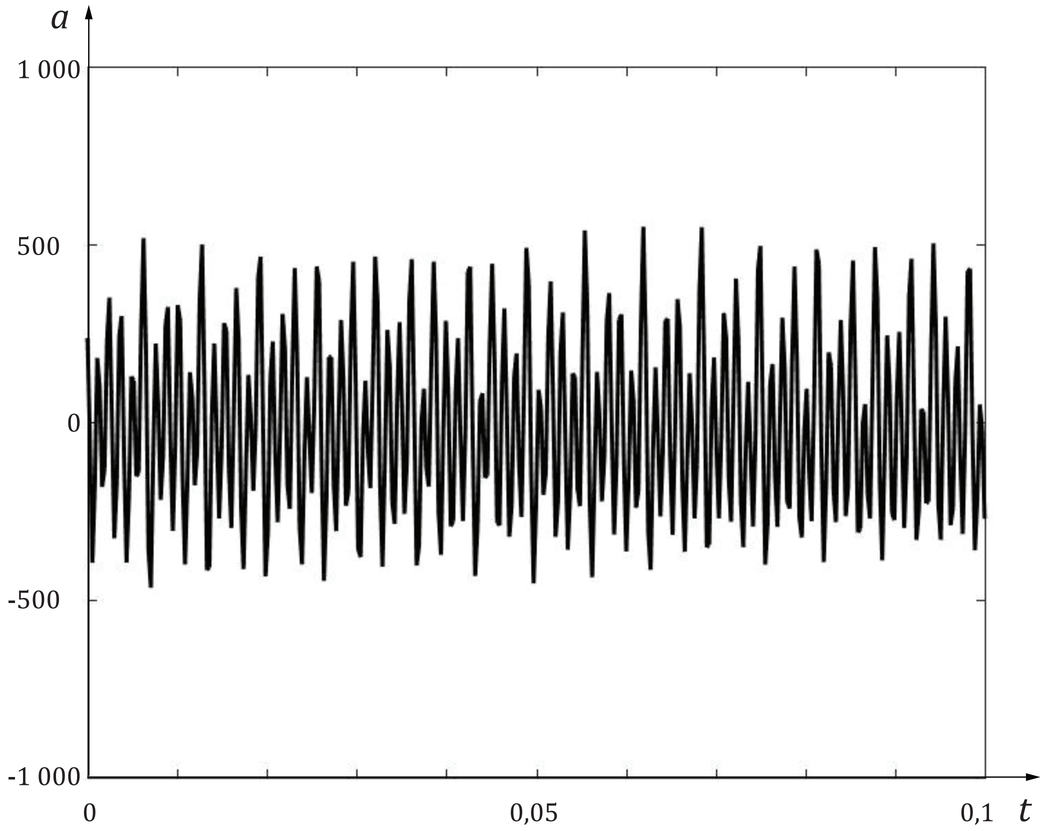
[a] Rectangular force window.

Figure 8 — Leakage errors caused by a force window

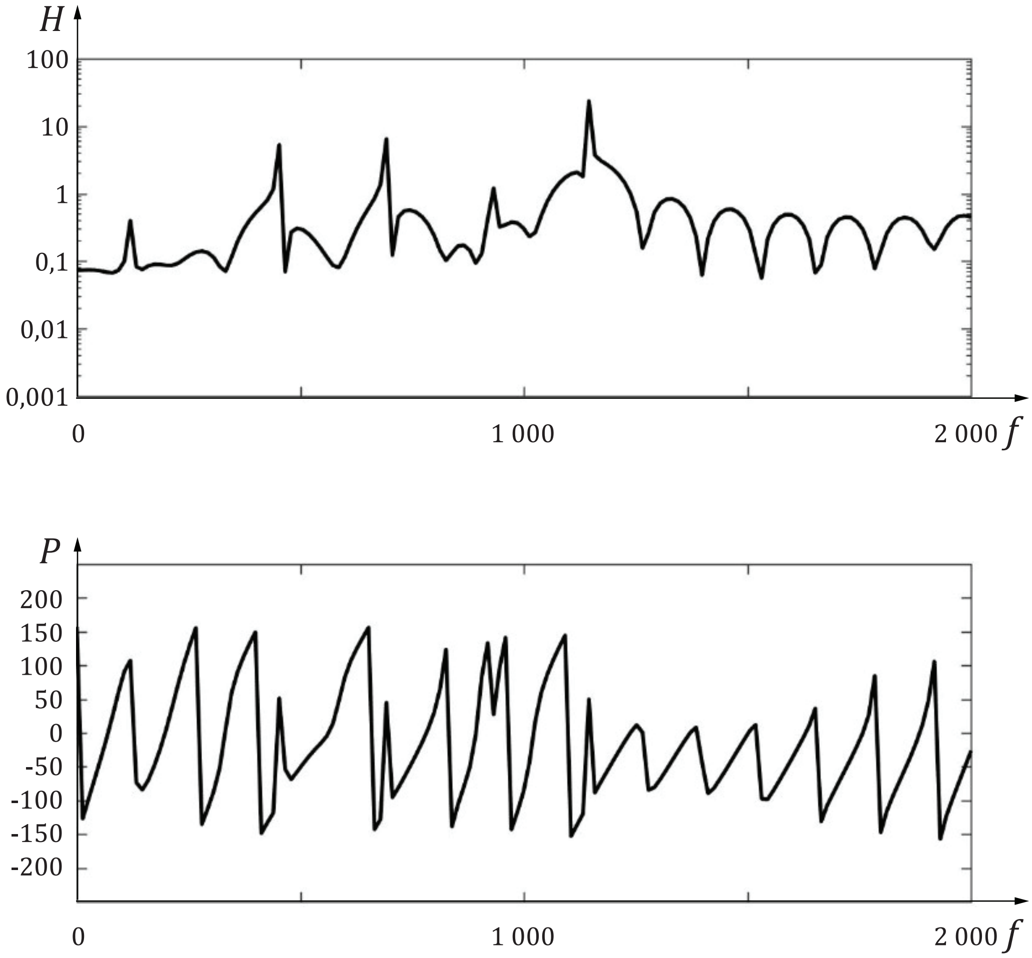
8.5.2 Windowing the response signals

As described in 8.3, the response signals should decay to about 1 % of their initial values at the end of the digital record in order to prevent truncation errors. A convenient check is to verify that the peak response signal at the midpoint of the record is about 10 % of the highest peak response. For lightly damped structures, it can be impossible (or undesirable) to achieve this condition directly because it requires an impractically large block size or a very narrow bandwidth zoom in the Fourier analyser. If such fine frequency resolution is not otherwise required by the application, then a better approach is to add a known amount of artificial decay to the response data prior to Fourier processing by means of a time-domain exponential decay window.

An exponential window has an initial value of unity and decreases exponentially to some final value at the end of the time record. Figure 9 shows a lightly damped response record and the corresponding frequency-response estimate. Figure 10 shows the same data after applying an exponential window which decays to 5 % of the initial value. The frequency response in Figure 9 exhibits the characteristic signs of DFT "leakage" errors: significant phase distortion and a somewhat noisy magnitude plot. Furthermore, the un-windowed frequency-response function underestimates the true magnitude of each resonance peak by an unpredictable amount that depends on the fraction of the total response for that particular vibration mode which has been truncated in the time record.



a) Acceleration response



b) Accelerance (acceleration/force magnitude and phase) without exponential window

Key

a acceleration response, m/s^2

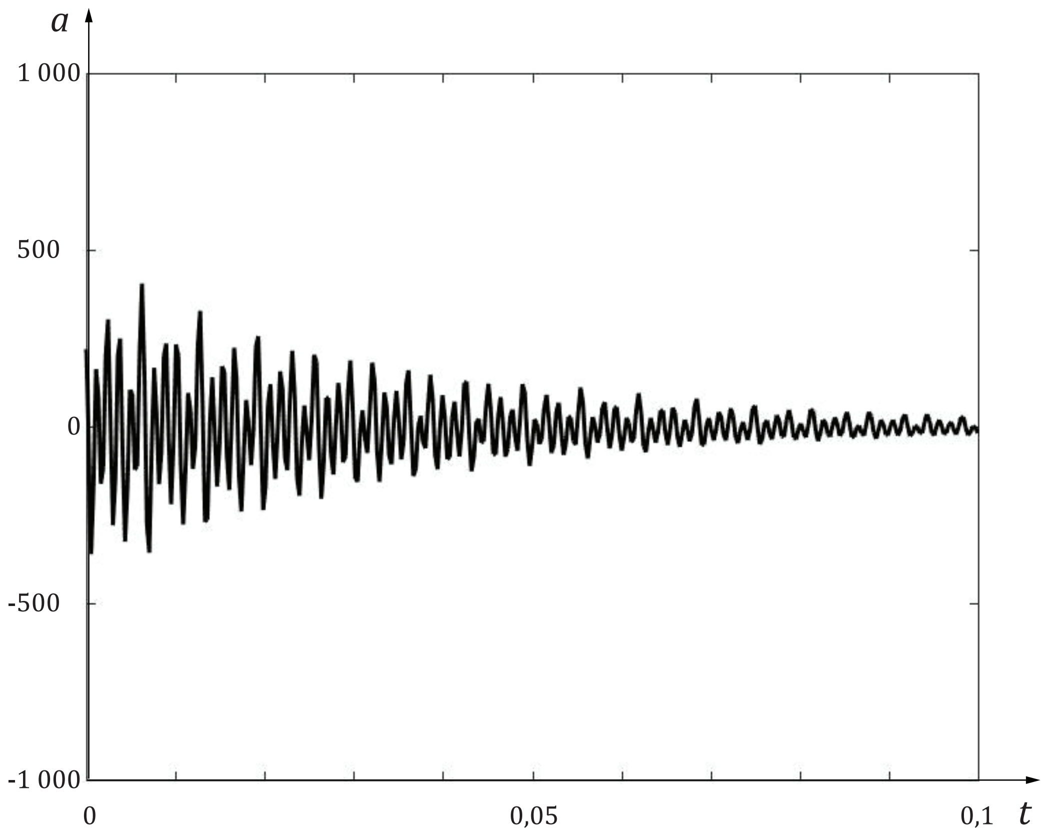
t time, s

H accelerance, m/(Ns^2)

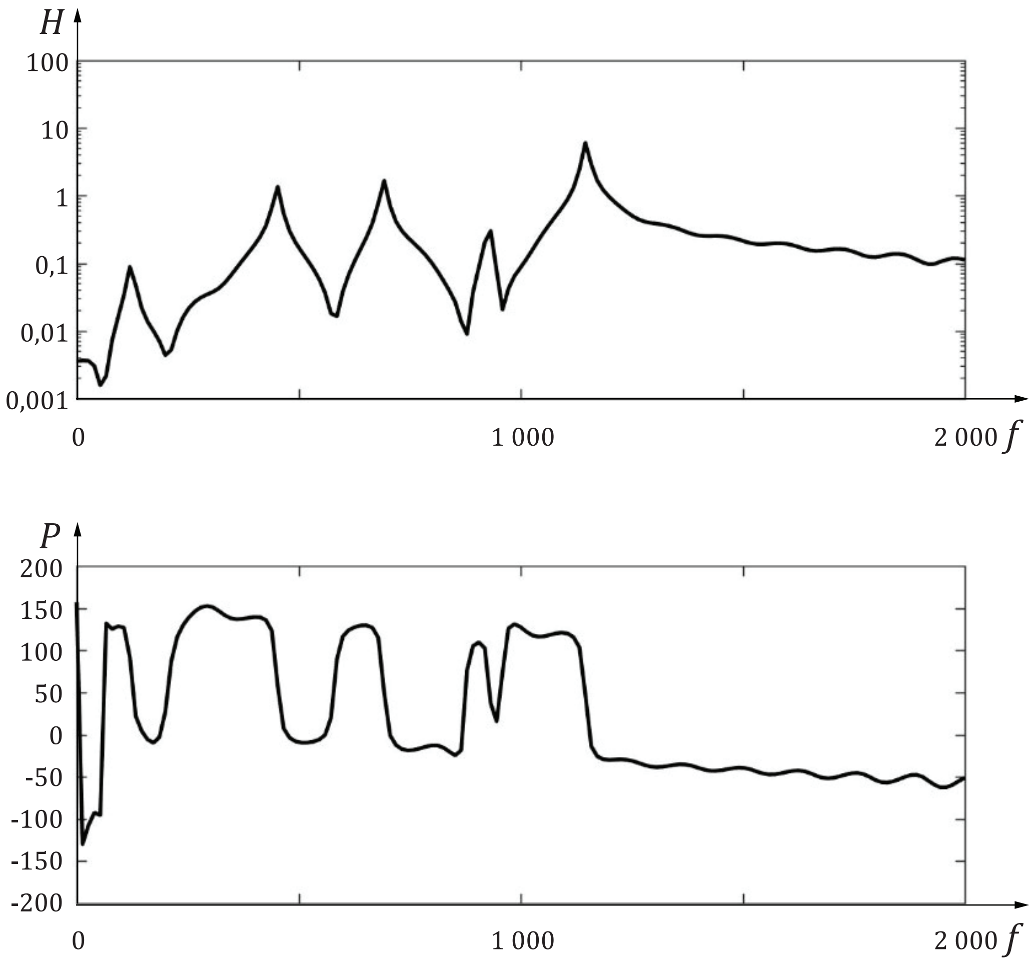
P phase, °

f frequency, Hz

Figure 9 — Un-windowed response and frequency-response function (leakage)



a) Acceleration response with exponential window



b) Accelerance (acceleration/force magnitude and phase) with exponential window

Key

a acceleration response, m/s^2

t time, s

H accelerance, m/(Ns^2)

P phase, degree

f frequency, Hz

Figure 10 — Exponentially windowed response and frequency-response function

Figure 10 shows a clearly marked reduction in distortion. However, all resonance peaks show reduced amplitude, which can be corrected by the procedure given in Annex A. This correction depends on determining the apparent damping of each vibration mode present in the (windowed) data, and then subtracting the known artificial damping due to the exponential window. As a general guideline, the response signal should decay naturally to 25 % or less of its initial magnitude within the digital record, otherwise the amplitude corrections become very sensitive to any error in the damping estimates.

Even if the time record is long enough to capture essentially all of the response data, the use of an exponential window can improve the signal-to-noise ratio of the measurement by giving increased weight to the high-amplitude portion of the response.

8.6 Averaging techniques

Frequency-domain averaging of data from several impacts at a fixed point may be performed in order to improve the estimate of the frequency-response function. This estimate can be obtained as the averaged cross-spectrum of the response and the force, divided by the averaged auto-spectrum of the force. Averaging also permits calculation of the coherence function (see 9.1).

In a low-noise environment, averaging three to five impacts is usually sufficient to verify data quality. A larger number of impacts may be used to reduce the effect of uncorrelated noise on the response signals. However, the impact method loses its speed advantage if a very large number of impacts need to be averaged, and so other excitation methods should be considered if the background noise cannot be reduced.

Make sure that the response of the structure has decayed below the limit of detection before applying the next impact for averaging; any residual “ringing” can interfere with the measurement of the subsequent response signals. For small or lightly damped structures, it is useful to damp out the structural response manually.

9 Tests for validity of the measurements

9.1 Coherence function

The coherence function is defined as the ratio of the square of the magnitude of the averaged cross-spectrum between the force and the response, to the product of the averaged auto-spectra of the force and of the response. The coherence function expresses the degree of linear relationship between the response and the force for each sampled frequency. The value of the coherence function is always between 1 and 0. If the FRF of a linear system were measured without error, the coherence function would equal 1. A coherence value less than 1 is an indication of possible poor quality of data.

The accuracy of a coherence estimate depends on both the number of data records which were averaged to obtain it and the true value of the coherence. If the true value is high (greater than 0,9), then only a few records (five to ten) are needed to achieve high statistical confidence in the accuracy of the estimate. Formulae for estimating errors are given in Reference [5].

NOTE 1 Low coherence at “anti-resonance” frequencies is not generally a cause for concern about data quality. At such frequencies, the structural response can be near the noise floor of the instrumentation, and the low coherence merely indicates the reduced signal-to-noise ratio.

Possible causes of low coherence for an impact measurement include:

a) noise in the force signal;

b) noise in the response signal;

c) variation in the location or direction of the impacts during averaging;

d) certain types of nonlinearity.

NOTE 2 Certain types of error are not indicated by the coherence function.

This is the case if the impact force is repeatable, resulting in deterministic errors, including:

a) leakage due to truncation of the response (inadequate frequency resolution);

b) structural nonlinearities;

c) signal clipping.

If low coherence is due to noise at the response signal (background vibrations), accurate unbiased measurement can still be made by a sufficiently high number of averages. (See ISO 7626-2:2015, Annex A.)

Noise in the input should be removed by an appropriate windowing technique since otherwise the frequency-response calculation is biased (see 8.5.1).

9.2 Repeatability check

After completing a series of mobility measurements, it is recommended that at least one of the initial measurements be repeated in order to verify that agreement is within acceptable limits. This test can indicate problems such as changes in the structure or its boundary conditions, variations due to temperature changes or changes in the measurement system calibration. If practical, this test should repeat the complete test setup and installation.

9.3 Reciprocity check

For a linear structure, the principle of dynamic reciprocity states that the transfer mobility between any two points should be unchanged if the excitation and response points are interchanged (symmetry of system matrices). Agreement between such pairs of measurements gives added confidence in the validity of the procedures employed; lack of agreement can indicate problems such as excessive mass loading by the response transducer(s) or certain types of nonlinearity.

9.4 Linearity check

Many types of nonlinearity can be detected by repeating the same mobility measurement using different amplitudes of excitation. If practical, the force amplitude should be changed by a factor of ten and any significant deviation between the resulting mobility measurements should be investigated.

9.5 Comparison with measurements using an attached exciter

In some cases, it can be desirable to perform a direct comparison with the same mobility measured using continuous excitation with an attached exciter. This procedure involves considerable additional equipment and setup time. It is not usually performed unless there is some doubt about the suitability of the test structure for impact excitation.

NOTE Refer to ISO 7626-2 when assembling electrodynamic shakers, in which the structural boundaries change, for example due to the fact that the flexural stiffness and the lateral stiffness of the coupling rod are not vanishingly small.

Annex A
(informative)

Correction of mobility measurements for the effects of exponential windowing

The use of an exponential window is often helpful in reducing the effects of leakage errors and noise in frequency-response measurements using impact excitation, as discussed in 8.5. However, such windowing has significant effects on the resulting mobility magnitudes. These effects can be accurately corrected by the procedure described below, provided that the data can be accurately fitted by a linear model and that the apparent damping of each mode in the frequency range of interest can be accurately determined. In a sense, this dependence on damping estimation methods places this technique outside the realm of pure measurement and into the domain of modal analysis. Although a discussion of damping estimation techniques is beyond the scope of this document, suitable parameter estimation capability is now widely available through a variety of curve-fitting methods.

Assume that the response-time history $x(t)$ is related to the input force $f(t)$ by a linear process having impulse response $h(t)$ and that the initial conditions are zero; i.e. the structure is initially at rest. Then $x(t)$ is given by the convolution integral as indicated in Formula (A.1):

$$x(t)=h(t)*f(t)=\int_0^t h(\tau)f(t-\tau)\mathrm{d}\tau \tag{A.1}$$

Multiplying both sides of Formula (A.1) by e^{-at} yields:

$$\mathrm{e}^{-at}x(t)=\int_0^t \mathrm{e}^{-a\tau}h(\tau)\mathrm{e}^{-a(t-\tau)}f(t-\tau)\mathrm{d}\tau \tag{A.2}$$

Formula (A.2) shows that if both the force- and response-time histories are multiplied by an exponential decay window function, then the impulse response which relates these windowed histories is the true impulse response multiplied by the same exponential decay function. The impulse response of a linear system is a superposition of terms of the form $A_r e^{s_r t}$, where s_r is the complex number whose real and imaginary parts are the decay rate and damped natural frequency, respectively, for the r^{th} mode of vibration, and A_r is a complex constant. Therefore, the effect of exponential windowing both force and response is to replace s_r with $(s_r - a)$ in the impulse-response function.

If exponential windowing is employed for a frequency-response function measurement and if $\hat{\zeta}_r$ is the damping factor for the r^{th} mode estimated from this measurement, then the true damping for mode r is given by Formula (A.3)

$$\zeta_r=\hat{\zeta}_r-a/\omega_r \tag{A.3}$$

where ω_r is the damped natural frequency in radians per second.

The corrected mobility is obtained by synthesis using the corrected damping values for all modes in the frequency range of interest. For lightly damped, well-separated modes, the peak amplitude is inversely proportional to the damping, so in this case the measured peak magnitude at mode r is multiplied by $\hat{\zeta}_r/\zeta_r$ to yield the true peak magnitude.

In practice, the exponential window is often applied only to the response-time history and not to the force-time history. Because of the very short duration of the impact-force signal, the effect of exponential windowing on the force can be closely approximated by multiplying the force by a constant equal to the window value at the instant of peak force. If the force peak occurs very close to the beginning of the digital record, this constant can be sufficiently close to unity to be safely ignored. If the operational calibration test of 7.2 is performed using the same windowing and pre-trigger as the mobility measurements, then this effect is automatically incorporated in the force calibration.

Bibliography

[1] ISO 7626-1:2011, *Mechanical vibration and shock — Experimental determination of mechanical mobility — Part 1: Basic terms and definitions, and transducer specifications*

[2] ISO 7626-2:2015, *Mechanical vibration and shock — Experimental determination of mechanical mobility — Part 2: Measurements using single-point translation excitation with an attached vibration exciter*

[3] Brown, D., Carbon, G. and Ramsey, K. *Survey of Excitation Techniques Applicable to the Testing of Automotive Structures,* Society of Automotive Engineers, Paper No. 770 029, 1977

[4] Halvorsen W., Brown D., Impulse Techniques for Structural Frequency Response Testing. *Sound Vibrat.* 1977 November

[5] Bendat, J. and Piersol, A. *Random Data: Analysis and Measurement Procedures,* John Wiley, 2010

[6] Ewins D., State-of-the-Art Assessment of the Mobility Measurement Techniques — Summary of Results. *Journal of the Society of Environmental Engineers*. 1981 March, **21** (1)

[7] Mitchell L., Improved Method for the Fast Fourier Transform (FFT) Calculation of the Frequency Response Function. *J. Mech. Des.* 1982, **104** pp. 277–279

[8] Sisson , Zimmermann , Martz , *Determination of Modal Properties of Automotive Bodies and Frames Using Transient Testing Techniques,* Society of Automotive Engineers. *Paper No.* 1973, **730** p. 502

[9] Brown D., Allemang R., Zimmermann R., Mergeay M., *Parameter Estimation Techniques for Modal Analysis,* Society of Automotive Engineers. *Paper No.* 1979, **790** p. 221

[10] Peterson E., Klosterman A. *Obtaining Good Results from an Experimental Modal Survey,* Society of Environmental Engineers Conference, November 1977

[11] Tabor R., Brown D., Vold H., Rocklin G. Exponential Window for Burst Random Excitation, *Proceedings of the Third International Modal Analysis Conference, January* 1985

[12] Sohaney R., Nieters J. Proper Use of Weighting Functions for Impact Testing, *Proceedings of the Third International Modal Analysis Conference, January* 1985

[13] Ewins, D. *Modal Testing: Theory and Practice,* Wiley, 1984

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