BS EN 62567:2013

BSI Standards Publication

# Overhead lines — Methods for testing self-damping characteristics of conductors

...making excellence a habit.™

## National foreword

This British Standard is the UK implementation of EN 62567:2013. It is identical to IEC 62567:2013.

The UK participation in its preparation was entrusted to Technical Committee GEL/7, Overhead electrical conductors.

A list of organizations represented on this committee can be obtained on request to its secretary.

Published by BSI Standards Limited 2013

ISBN 978 0 580 61689 1
ICS 29.060.01; 29.240.20

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 December 2013.

### Amendments/corrigenda issued since publication

| Date | Text affected |
|---|---|

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

# EN 62567

November 2013

ICS 29.060; 29.240.20

English version

# Overhead lines - Methods for testing self-damping characteristics of conductors
(IEC 62567:2013)

Lignes électriques aériennes -
Méthodes d'essai des caractéristiques d'auto-amortissement des conducteurs
(CEI 62567:2013)

Freileitungen -
Methoden zur Prüfung der Eigendämpfungseigenschaften von Leitern
(IEC 62567:2013)

This European Standard was approved by CENELEC on 2013-10-17. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

CENELEC
European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

**CEN-CENELEC Management Centre: Avenue Marnix 17, B - 1000 Brussels**

## Foreword

The text of document 7/629/FDIS, future edition 1 of IEC 62567, prepared by IEC/TC 7 "Overhead electrical conductors" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62567:2013.

The following dates are fixed:

| | | |
|---|---|---|
| • latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement | (dop) | 2014-07-17 |
| • latest date by which the national standards conflicting with the document have to be withdrawn | (dow) | 2016-10-17 |

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

## Endorsement notice

The text of the International Standard IEC 62567:2013 was approved by CENELEC as a European Standard without any modification.

# Annex ZA
(normative)

## Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

| Publication | Year | Title | EN/HD | Year |
|---|---|---|---|---|
| IEC 60050-466 | 1990 | International electrotechnical vocabulary (IEV) - Chapter 466: Overhead lines | - | - |
| IEEE Std. 563 | 1978 | IEEE Guide on conductor self-damping measurements | - | - |
| IEEE Std. 664 | 1993 | IEEE Guide for laboratory measurement of the power dissipation characteristics of aeolian vibration dampers for single conductors | - | - |

# CONTENTS

# INTRODUCTION

Conductor self-damping is a physical characteristic of the conductor that defines its capacity to dissipate energy internally while vibrating. For conventional stranded conductors, energy dissipation can be attributed partly to inelastic effects within the body of the wires (hysteresis damping at the molecular level) but mostly to frictional damping, due to small relative movements between overlapping individual wires, as the conductor flexes with the vibration wave shape.

Self-damping capacity is an important characteristic of the conductors for overhead transmission lines. This parameter is a principal factor in determining the response of a conductor to alternating forces induced by the wind.

As the conductor self-damping is generally not specified by the manufacturer, it can be determined through measurements performed on a laboratory test span. Semi-empirical methods to estimate the self-damping parameters of untested conventional stranded conductors are also available but often lead to different results. Further, a great variety of new conductor types is increasingly used on transmission lines and some of them may have self-damping characteristics and mechanisms different from the conventional stranded conductors.

A “Guide on conductor self-damping measurements” was prepared jointly in the past by the IEEE Task Force on Conductor Vibration and CIGRE SC22 WG01, to promote uniformity in measuring procedures. The Guide was published by IEEE as Std. 563-1978 and also by CIGRE in Electra n°62-1979.

Three main methods are recognized in the above documents and divided into two main categories which are usually referred to as the "forced vibration" and ''free vibration" methods.

The first forced vibration method is the “Power [Test] Method” in which the conductor is forced into resonant vibrations, at a number of tunable harmonics, and the total power dissipated by the vibrating conductor is measured at the point of attachment to the shaker.

The second forced vibration method, known as the “Standing Wave Method” or more precisely “Inverse Standing Wave Ratio [Test] Method” (ISWR), determines the power dissipation characteristics of a conductor by the measurement of antinodal and nodal amplitudes on the span, for a number of tunable harmonics.

The free vibration method named “Decay [Test] Method” determines the power dissipation characteristics of a conductor by measuring, at a number of tunable harmonics, the decay rate of the free motion amplitude following a period of forced vibration.

Several laboratories around the world have performed conductor self-damping measurements in accordance with the above mentioned Guide. However, large disparities in self-damping predictions have been found among the results supplied by the various laboratories. The causes of these disparities have been identified into five main points:

1) The different test methods adopted for the self-damping measurements.
2) The different span end conditions set up in the various test laboratories (rigid clamps, flexure members, etc.)
3) The different types of connection between the shaker and the conductor (rigid or flexible) and the different location of the power input point along the span.
4) The different conductor conditioning before the test (creep, running in, etc.)
5) The different manufacturing processes of the conductor.

# OVERHEAD LINES – METHODS FOR TESTING SELF-DAMPING CHARACTERISTICS OF CONDUCTORS

## 1 Scope

The scope of this Standard is to provide test procedures based on the above-mentioned documents and devoted to minimize the causes of discrepancy between test results, taking into consideration the large experience accumulated in the last 30 years by numerous test engineers and available in literature, including a CIGRE Technical Brochure specifically referring to this standard (see Bibliography).

This Standard describes the current methodologies, including apparatus, procedures and accuracies, for the measurement of conductor self-damping and for the data reduction formats. In addition, some basic guidance is also provided to inform the potential user of a given method's strengths and weaknesses.

The methodologies and procedures incorporated in this Standard are applicable only to testing on indoor laboratory spans.

## 2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-466:1990, *International Electrotechnical Vocabulary. Chapter 466: Overhead lines*

IEEE Std. 563-1978, *IEEE Guide on conductor self-damping measurements*

IEEE Std. 664-1993, *IEEE Guide for laboratory measurement of the power dissipation characteristics of aeolian vibration dampers for single conductors*

## 3 Terms and definitions

For the purpose of this International Standard, the definitions of the International Electrotechnical Vocabulary (IEV) apply, in particular IEC 60050-466. Those which differ or do not appear in the IEV are given below.

### 3.1
**conductor self-damping:**
the self-damping of a conductor subjected to a tensile load $T$ is defined by the power $P_\mathrm{c}$ dissipated per unit length by the conductor vibrating in a natural mode, with a loop length $\lambda/2$, an antinode displacement amplitude $Y_0$ and a frequency $f$

### 3.2
**node**
in a vibrating conductor, nodes are the points in which the vibration amplitude is the smallest

### 3.3
**anti-node**
in a vibrating conductor, anti-nodes are the points in which the vibration amplitude is the greatest

## 4 Symbols and units

| | | |
|---|---|---|
| $A$ | forcing point transverse acceleration, single amplitude | m/s$^2$ |
| $a_\mathrm{n}$ | vibration amplitude at the n$^\mathrm{th}$ node | mm |
| $D,d$ | diameter of the conductor | m |
| $\delta$ | logarithmic decrement | |
| $E_\mathrm{diss}$ | total energy dissipated by the vibrating conductor | Joule |
| $E_\mathrm{kin}$ | total kinetic energy of the vibrating conductor | Joule |
| $F$ | single amplitude exciting force | N |
| $f$ | vibration frequency | Hz |
| $h$ | non dimensional viscous damping coefficient | |
| $L$ | free length of the test span | m |
| $\lambda$ | wavelength | m |
| $\lambda/2$ | loop length | m |
| $m$ | conductor mass per unit length | kg/m |
| $n$ | number of vibrating loops in the span | |
| $n_\mathrm{c}$ | number of vibration cycles | |
| $n_\mathrm{kj}$ | number of loops between loop *k* and loop *j* | |
| $P$ | power dissipated by the conductor | mW |
| $P_\mathrm{c}$ | power dissipated by the conductor per unit length | mW/m |
| $P_\mathrm{j}$ | power dissipated by the conductor, measured at loop j | mW |
| $P_\mathrm{k}$ | power dissipated by the conductor, measured at loop k | mW |
| $\theta_\mathrm{a}$ | phase angle between force and acceleration | deg |
| $\theta_\mathrm{d}$ | phase angle between force and displacement | deg |
| $\theta_\mathrm{v}$ | phase angle between force and velocity | deg |
| $S_\mathrm{j}$ | Inverse standing wave ratio (ISWR) at loop j | |
| $S_\mathrm{k}$ | Inverse standing wave ratio (ISWR) at loop k | |
| $S_\mathrm{n}$ | Inverse standing wave ratio (ISWR) at the n$^\mathrm{th}$ loop | |
| $T$ | conductor tension | N |
| $V$ | forcing point transverse velocity, single amplitude | m/s |
| $V_\mathrm{n}$ | vibration velocity at the n$^\mathrm{th}$ antinode – peak value | m/s |
| $\omega$ | circular frequency | rad |
| $Y_\mathrm{a}$ | single antinode amplitude at the first decay cycle | mm |
| $Y_\mathrm{f}$ | vibration single amplitude at the driving point | mm |
| $Y_\mathrm{n}$ | vibration single amplitude at the n$^\mathrm{th}$ antinode | mm |
| $Y_\mathrm{o}$ | vibration single amplitude at antinode | mm |
| $Y_\mathrm{z}$ | single antinode amplitude at the last decay cycle | mm |
| $\sqrt{\mathrm{Tm}}$ | characteristic impedance of the conductor | N s/m |

## 5 Test span arrangements

### 5.1 General

The laboratory test spans for conductor self-damping measurements are generally built indoor in still air areas where the variation of ambient temperature is minimal or can be suitably controlled. Ambient temperature variations up to 0,2 °C/h are considered acceptable.

The free span length L should preferably be at least ten times longer than the longest loop length used in the tests. For consistent results, a span length greater than 40m is recommended but satisfactory results can be obtained with spans in the range of 30m. For shorter spans, the influence of the termination losses and the distribution of the tensile load between the conductor strands may be critical.

The test span shall be strung between two massive blocks with a weight not lower than 10 per cent of the ultimate tensile strength of the largest conductor to be tested. Each block should be a single piece, generally made of steel reinforced concrete, and preferably be common or solidly connected with the concrete floor. The stiffness of these blocks should be as high as possible in order to minimize the losses and provide the maximum reflexion of the waves.

An example of laboratory test span layout is shown in Figure 1.

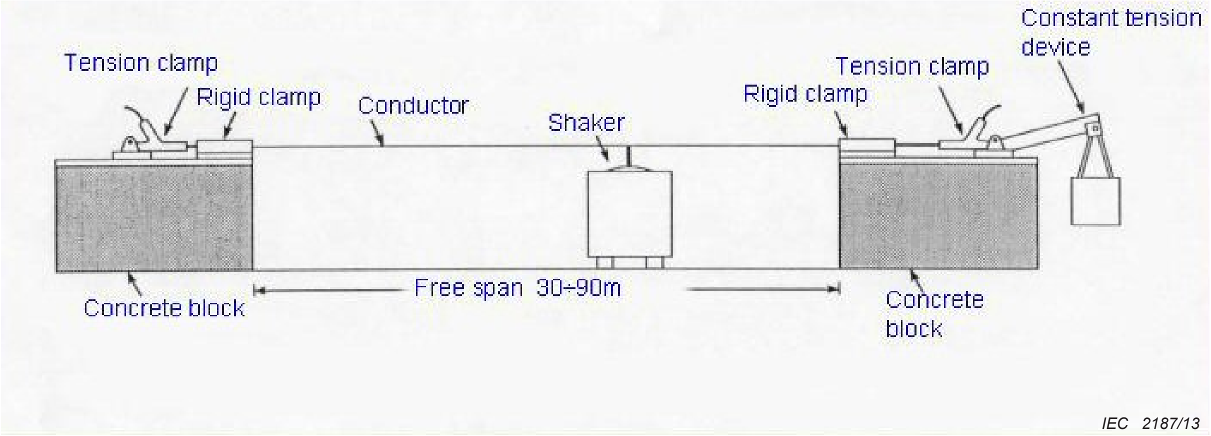


**Figure 1 – Test span for conductor self-damping measurements**

### 5.2 Span terminations

The test span should have the capability of maintaining a constant conductor tension. Hydraulic and pneumatic cylinders, springs, threaded bars and pivotal balance beams have been used successfully.

A rigid non-articulating square faced clamp similar to that shown in Figure 2 shall be used to minimize energy dissipation by the termination fixture. An example of a typical termination design is also provided in Figure 3 of IEEE Std. 563-1978. Terminating fixtures and rigid clamps shall be of sufficient stiffness to ensure that energy losses do not occur beyond the extremities of the free span.

Rigid end clamps (also called heavy clamps), equal to or up to ten times longer than the conductor diameters and with groove diameters not exceeding by more than 0,25 mm the diameter of the conductor, have given good results. Generally, the clamp groove is dimensioned for the biggest conductor to be tested and a set of sleeves is made available to accommodate smaller conductor diameters.

The rigid clamps shall not be used to maintain tension on the span. However, the rigid clamps, once closed, will retain some load. Consequently, the tension devices cannot fully control the conductor tension. Subsequent adjustments, if necessary, shall be performed only after releasing the rigid clamps.

It is very important to have a good alignment between tension clamps and rigid clamps in the horizontal direction. In the vertical direction, in order to eliminate the static bending of conductor at the rigid clamp departure, it may be necessary to incline the rigid clamps following the catenary angle. This practice, when necessary, would avoid any change in tensile load when closing or opening the clamps.


IEC 2188/13

**Figure 2 – Rigid clamp**

On a laboratory test span, normally, the wave shape of the end loops differs from the shape of the free loops and the end loop dissipation is greater than free loop dissipation. As the energy dissipation of the conductor is, to a first approximation, proportional to the square of its curvature, it is easy to explain the large dissipation of energy near the end of the span. The effect is more noticeable at low frequencies where the end loops constitute a higher proportion of the total number of loops. It further restricts the usefulness of very short indoor test spans.

Preference should be given to a test arrangement which would minimize energy dissipation at the span end terminations. If there is uncertainty about this, the energy should be assessed and eventually accounted for, unless using the ISWR method.

The termination losses may be minimized by terminating the conductor by a flexure member, such as a wide, flat bar of sufficient strength to accommodate the span tension but also flexible enough in the vertical direction to allow it to bend readily and to avoid bending the conductor through a sharp radius of curvature where it would normally enter the clamp. This procedure has the undesirable effect, though, of including the end termination in the test span. An example of flexible cantilever is provided in Figure 4 of IEEE Std. 563-1978.

### 5.3 Shaker and vibration control system

The vibration exciter used for these tests is generally an electro-dynamic shaker (Figure 3). Hydraulic actuators are also used.

Modal shakers having light armature and linear bearings can be used to excite resonance modes of the conductor with minimal distortion of the natural mode shape and to produce virtually zero stiffness and zero damping in the direction of the movement.

The shaker shall be able to provide a suitable sinusoidal force to the test span. The alternating movement provided by the shaker shall be simple harmonic with a distortion level of less than 5 %.

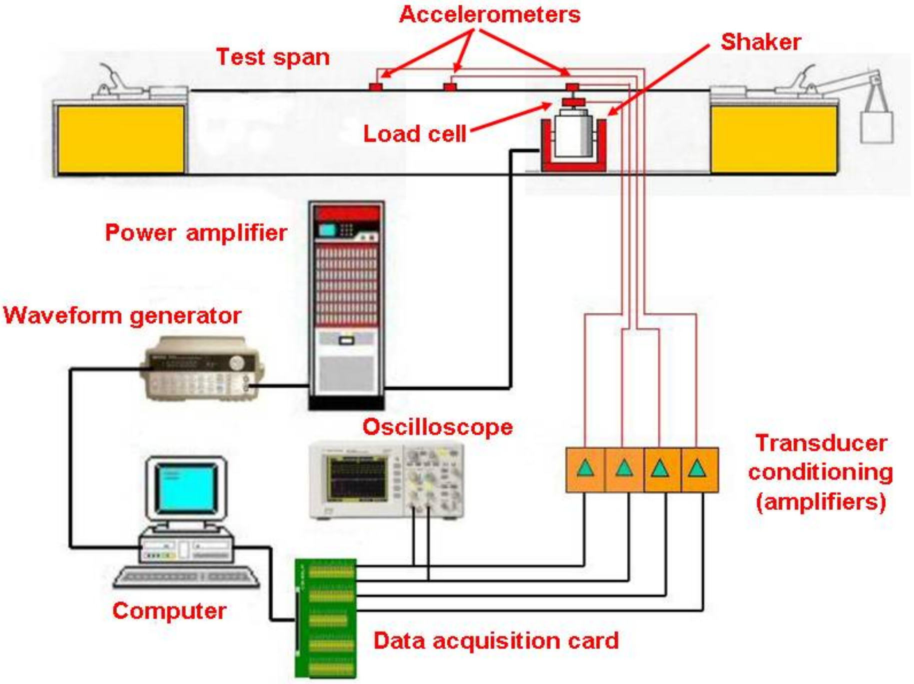
Vibration amplitude and frequency shall be controllable to an accuracy of ± 2 % and frequency shall be stable within 0,001 Hz.

IEC 2189/13

Figure 3 – Electro-dynamic shaker

The use of computers and dedicated software for the shaker control and for the data acquisition, reduction and elaboration is considered as a normal practice.

An example of the layout for the conductor self-damping measurements, fully equipped to perform the conductor self-damping measurements with the methods outlined in this standard, is shown in Figure 4.



IEC 2190/13

**Figure 4 – Layout of a test stand for conductor self-damping measurements**

## 5.4 Location of the shaker

The most used position of the shaker is within one of the end loops of the span, but not necessarily at an anti-node. This location also makes it possible to excite greater amplitudes than the maximum travel of the shaker even if a rigid connection between the shaker and the conductor is used.

The near end location makes it possible to excite odd numbers of loops, as well as even. Although some span symmetry may be lost due to the presence of the shaker, a centre free loop will be present for the odd loop excitations. This often makes it possible to conduct amplitude measurements within the centre loop without being forced to relocate the transducer for each frequency investigated.

The shaker should be located at a distance from the rigid clamp which is less than the calculated loop length of the span at the highest test frequency. This will ensure that whole loops will not be forced to occur between the shaker and the nearest span extremity, because this may cause erroneous test results. It is preferably to identify a location of the shaker that can be maintained unchanged for the whole test on one conductor. A wide range of conductor sizes has been tested with the shaker at a fixed distance from the end clamp of 0,8 to 1,2 m.

## 5.5 Connection between the shaker and the conductor under test

### 5.5.1 General

In the artificial excitation of the indoor test span, the armature of the shaker can be connected to the test span either rigidly or by the use of a flexible connection. In any case, the fixture shall be as light as possible in order to avoid the introduction of unwanted inertial forces and to prevent that, at the higher frequencies, the force needed to vibrate that mass plus the shaker armature will be beyond the capability of the shaker system.

To avoid distortion of the mode shape in the conductor vibration, the clamp mass must be as low as possible and, in resonance conditions, the phase between force and acceleration, at the driving point, must be as close as possible to 90 °. In this case, the force applied by the shaker has its minimum and equals the damping force. For angles different from 90 °, inertia and elastic components are also present and can give rise to distortions.

The shaker connection shall be instrumented for force and vibration level measurements. The latter is generally made using accelerometers but also velocity transducers and displacement transducer can be used.

### 5.5.2 Rigid connection

Rigidly fixing the shaker to the conductor (Figure 5) has a tendency to create distortion in the standing wave vibration. Care should be taken when establishing span resonance to minimize this effect.

**Figure 5 – Example of rigid connection**

Using a rigid connection, the vibration exciter becomes a part of the system being measured; if the mass of the moving system within the shaker is high, conductor distortion is induced in that portion of the span where the shaker is attached.

This changes the length of the loop to which the shaker is attached and is indicative of localized inertial and damping effects. The effect of attaching the shaker to the conductor should not change the loop length in which the attachment is made by more than 10 %. An attached mass of less than 20 % of the mass per unit length of the conductor is normally satisfactory. However, this can only be achieved using modal shakers or adopting a flexible connection as described in the following paragraph. Otherwise, the ISWR method, that is not sensitive to localized effects at the shaker as well as in end loops, should be used.

### 5.5.3 Flexible connection

Spring steel bands are often used to reduce distortion of the loop where the shaker is attached and to allow different conductor amplitudes at the drive point than the amplitude of the shaker. Suitable flexibility should be present in all directions in order to:

1) uncouple the shaker from the conductor so that possible misalignment between the centre of the shaker table and the point of attachment of the conductor can be accommodated and will not risk to damage the shaker armature;
2) prevent the shaker table from being driven by the conductor in resonant conditions where conductor vibration amplitude can be higher than the shaker amplitude;
3) avoid the introduction of additional inertial and damping effects due to the shaker armature and conductor attachment.

The stiffness of the springs in the excitation direction should be empirically determined in accordance with the conductor stiffness and mass. The spring should be soft enough to uncouple the conductor from the shaker but still able to transmit to the conductor enough force to excite vibration at the required amplitude.

An example of a flexible connection equipped with force and acceleration transducers is shown in Figure 6.

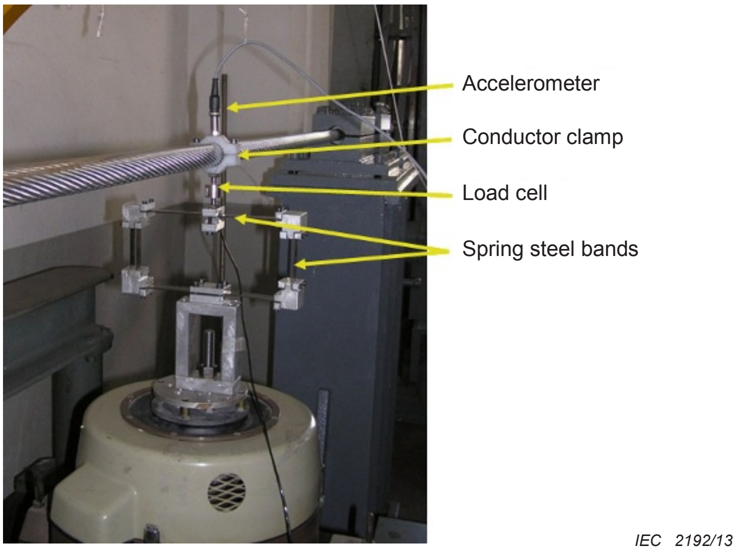


**Figure 6 – Example of flexible connection**

## 5.6 Transducers and measuring devices

### 5.6.1 Type of transducers

The following transducers are used for the self-damping measurements:

A. Load cells: to measure the force transmitted by the shaker to the conductor.
B. Accelerometers, velocity transducers and displacement transducers: to measure the level of vibration.

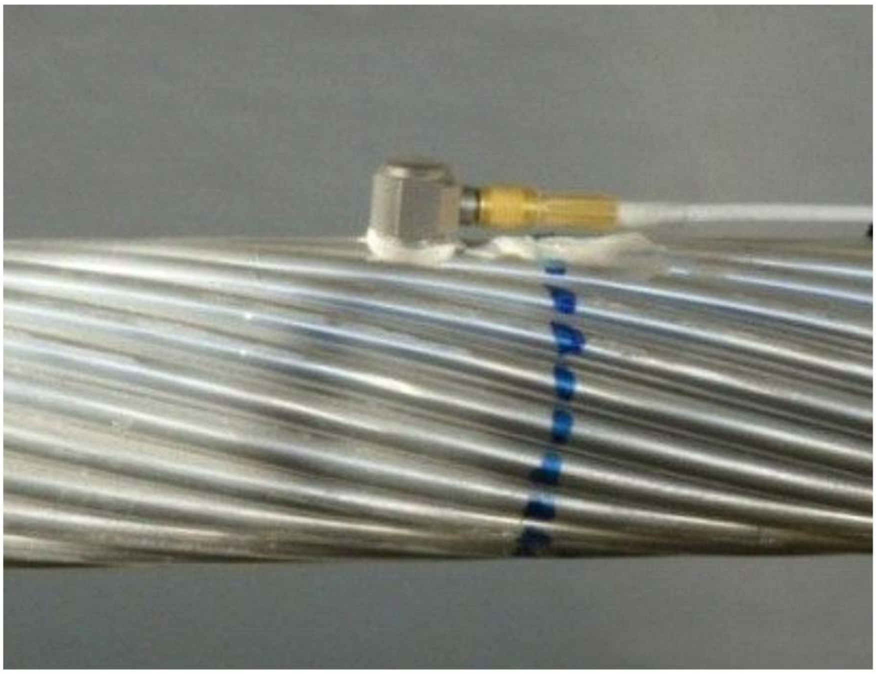
In addition, strain gauges are sometimes used to control the tension of the individual wires of the outer layer and temperature probes may be used for monitoring the ambient and/or conductor temperature.

There is no limitation or preference regarding the working principle of the transducers, providing their mass is small enough in order not to interfere with the system. Miniature load cells and miniature accelerometers (Figures 6, 7 and 8) are most commonly used for in-span measurements.

Contactless displacement transducers (laser or eddy current based) have also been used for measurements of node and antinode amplitudes, especially with small and light conductors.

Using transducers having a different working principle, for example a piezoelectric accelerometer and a strain gauge load cell, it is possible to have a phase shift between the two signals due to the different response time of the two transducers. This phase shift is frequency dependant and shall be taken into account in the determination of the phase angle between the measured quantities at each tunable vibration mode. A procedure to calculate the phase shift at each test frequency is presented in Annex D.

In a computer controlled test system, the data acquisition software can be set up to perform automatically the phase shift correction. In any case, for the sake of simplicity, it is recommended to use transducers having the same working principle so that no phase shift correction will be required.



IEC 2193/13

**Figure 7 – Miniature accelerometer**

### 5.6.2 Transducer accuracy

All the transducers used for the tests shall be checked for phase accuracy and linearity over the anticipated testing frequency range. The transducers shall be mounted on a shaker table and a small mass shall be rigidly attached on the force transducer. The transducers shall be shaken at all proposed test frequencies, and at approximately the amplitudes chosen for the conductor test. Correct operation of the transducers is demonstrated by two criteria: (1) the phase angle between force and acceleration (or displacement) should be at or near zero degrees and (2) the ratio of force to acceleration (F/A) should be constant at all frequencies and amplitudes. F/A, is the effective mass installed on the force transducer. If velocity transducers are used, the phase angle between force and velocity should be at or near 90 degrees and acceleration can be obtained by the derivative of the velocity signal acquired.

Deviations of the phase values up to ± 5 degrees are acceptable.

The test verifies (1) that there is no spurious phase shifting due to effects of fixtures, transducers and signal conditioning devices and (2) that the transducers are linear with respect to frequency and vibration amplitude. This is important especially for the transducers used for the measurement of the power imparted to the conductor by the shaker.

## 6 Conductor conditioning

### 6.1 General

Unless otherwise specified, the conductor under test shall be unused.

Before the installation on the test span, any looseness in the conductor layers should be worked out.

After that, the conductor is clamped and should be conditioned as described in the following.

### 6.2 Clamping

The terminations of the conductor under test can be made using compression dead end joints, or bolted dead end clamps. Wedge type tension clamps and potted (resin) terminations can also be used.

If compression end fittings are used, then they shall be reverse compressed (starting from the clamp mouth rather than from the end of the conductor) to prevent looseness from being worked back into the span.

### 6.3 Creep

After the installation of an unused conductor on the test span, a pre-stretching shall be performed in order to accomplish most of the metallurgic creep and the geometrical settlement of the conductor and distribute the tensile load more uniformly in the conductor strands. The pre-stretching consists in keeping the conductor at a tension equal or higher than the test tension for period of time, generally 12 to 48 hours. The tension to be applied during the preconditioning shall be established in accordance with the service parameters of the conductor.

The preconditioning will be considered sufficiently settled when the tension of the still conductor does not change more than 3 to 4 % in 30 minutes at constant room temperature.

The conductor shall be submitted to this preconditioning without clamping it into the end rigid clamps.

### 6.4 Running-in

When a conductor is unused its self-damping is not constant but varies with the accumulating vibration cycles. This variation may be in the order of 20-40 % during the first 30-60 minutes of vibration. A “running-in” is considered necessary to stabilize the conductor self-damping. This consists of vibrating the conductor at a fixed frequency, or with a swept frequency in a limited frequency range, at the maximum amplitude considered for the self-damping measurements. Power measurements should be performed every 15 minutes and the running in will be considered completed when the difference between two consecutive measurements will not exceed 3 to 4 %.

## 7 Extraneous loss sources

Apart of the main energy dissipation due to the vibration of the conductor at a natural frequency, some other energy losses take place in the test span. The source of these extraneous losses has to be recognized and, if possible, eliminated or reduced to the minimum. They are:

- Conductor deformation induced by the device used to force conductor vibration.
- Conductor deformation at span extremities due to the clamping system.
- Aerodynamic losses due to the conductor vibration in still air. The contribution of the aerodynamic damping to total damping may not be negligible at low frequency but generally it is reduced practically to zero at high frequency. Aerodynamic losses can be calculated according to the method reported in Annex C and subtracted, if required, from the measured losses.
- Torsional, longitudinal and transversal motions other than the driven motion. Torsional and longitudinal motions may be induced through coupling with the forced transversal motion. Test frequencies where this occurs shall be skipped. Torsional modes can also be excited by the asymmetry of the conductor and by misalignment of the shaker. Transversal motions at low frequency can be excited by air movements or by accidental contact with the conductor. The vibrating conductor shall be visually controlled to verify the absence of these kinds of motion.
- Longitudinal support damping due to the insufficient rigidity of the terminating fixtures which results in the transmission of conductor vibration power into the tensioning apparatus where some of that power may be dissipated.

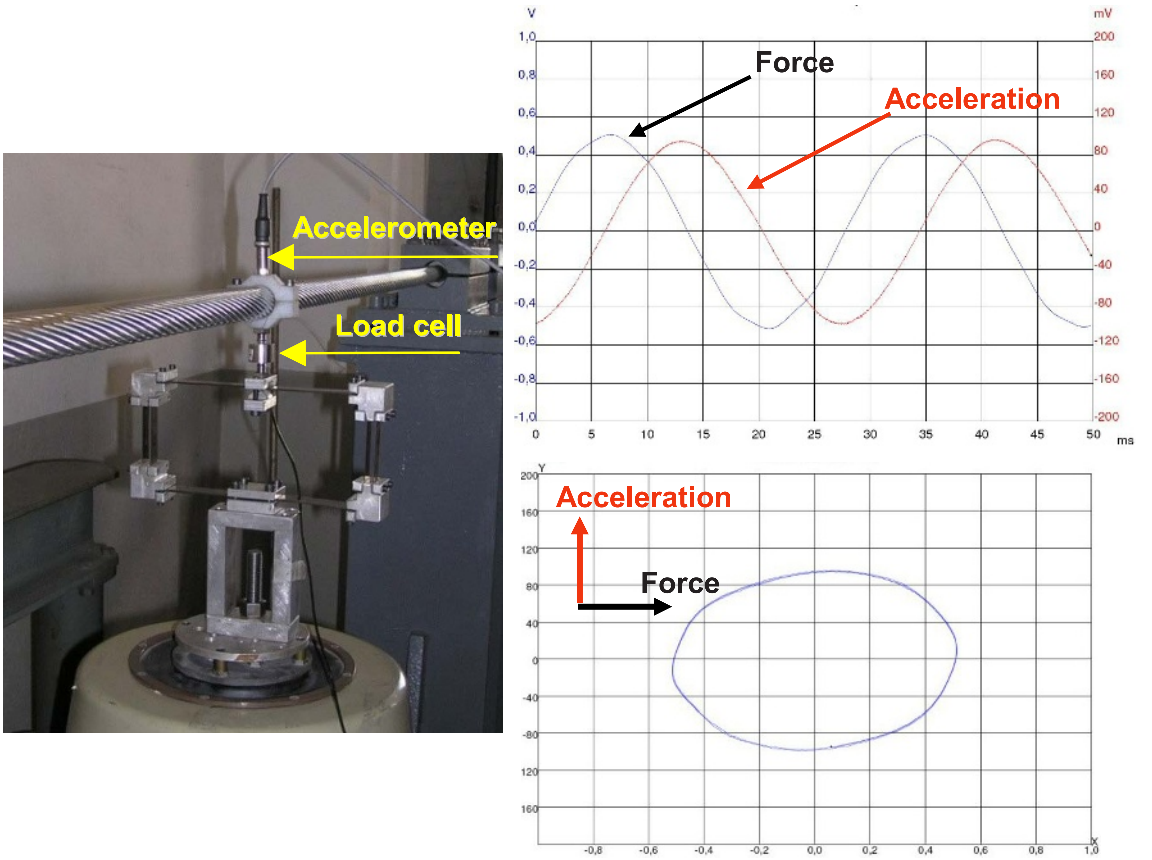
## 8 Test procedures

### 8.1 Determination of span resonance

All the test methods described in this Standard require that the conductor should reach a resonant condition.

To find the system resonance, the shaker is operated at a trial power setting and the frequency control is adjusted to provide for maximum displacement of the conductor at an antinode. Then the shaker power controls are adjusted to provide the correct loop amplitude/ velocity at an antinode. Frequency is fine-tuned to maximize loop amplitude. If necessary, the shaker power is again adjusted to provide the desired loop amplitude. System resonance is found when adjustments of the frequency control no longer results in an increase in loop amplitude. Testing is performed when the standing wave is stable at the correct amplitude/velocity.

An alternative method make use of the measurements/monitoring of force and acceleration (or velocity) and their relative phase angle at the shaker attachment. The frequency is tuned until the phase angle between the force and the acceleration signals is stable at or near 90° (see Figure 8) or the phase angle between the force and the velocity signals is stable at or near zero degrees. In practice, the force signal may be distorted and filtering will be needed to obtain a valid phase measurement.



IEC 2194/13

**Figure 8 – Resonant condition detected by the acceleration and force signals**

The vibration frequencies to be considered during the tests should cover the spectrum corresponding to a wind velocity range of 1 to 7 m/s (3,6 to 25,2 km/h) unless otherwise specified. Equation (A.1), in Annex A, can be used to convert wind velocity into vibration frequency. It is recommended that measurements be made at each tunable frequency; this criterion may be modified in accordance with the results desired by the end user but, in any case, minimum of 10 test frequencies shall be utilized.

The natural frequencies of the span may be estimated by using the following equation:

$$f = \frac{n}{2L} \times \sqrt{\frac{T}{m}} \qquad (1)$$

Conductor stiffness and the influence of the shaker on the span may modify the vibration modes, and thereby change the natural frequencies. However, equation (1) provides a good starting point for finding resonances.

### 8.2 Power Method

The power method determines the dissipation characteristics of a conductor by the measurement of the force and the vibration level imparted to the test span at the point of attachment to the shaker.

The conductor, tensioned on the experimental span, is forced to vibrate at one of its resonant frequencies, with both amplitude and frequency being controlled by means of the driving system.

Due to the general non-linear characteristics of the conductor response it may not always be possible to produce pure sinusoidal signals at resonance. The frequency components of the signal, other than the fundamental component, shall be filtered out. If analog filtering is used, the signals of both the force and the vibration level transducers shall be filtered and the filters shall be matched for phase and gain. Alternatively, a suitable two-channel Fast Fourier Transform Analyser or equivalent software may be used.

When a stationary condition is reached, the energy introduced by the shaker to the conductor, over one cycle of vibration, is equal to that dissipated by the span. The energy introduced in the conductor, and largely dissipated by its self-damping mechanism, is determined by measuring the force $F$ acting between the conductor and the shaker and the displacement of the driving point $Y_{\mathrm{f}}$. The result is then given by the formula:

$$E_{\mathrm{diss}} = \pi \times F \times Y_{\mathrm{f}} \times sin\ \theta_{\mathrm{d}} \qquad (2)$$

The test procedure is as follows:

- Establish span resonance beginning at the first tunable harmonic within the prescribed frequency range (minimum of ten loops).
- Measure and record the vibration frequency.
- Locate a mid-span antinode.
- Adjust the antinodal amplitude to the prescribed level and record this value.
- Record the input force and acceleration (or velocity or displacement) and their phase angle differential at the driving point.
- Measure and record the free loop length.
- Proceed to the next tunable harmonic frequency.
- Continue this procedure until the upper end of the required frequency range has been reached.
- Following the acquisition of data, the power dissipated by the conductor can be calculated from the following equation:

$$P = \frac{1}{4 \times \pi \times f} \times F \times A \times sin\ \theta_{\mathrm{a}} \qquad (3)$$

If a velocity transducer is used for the data acquisition, then the power dissipated by the conductor can be calculated from the following equation:

$$P = \frac{1}{2} \times F \times V \times cos\ \theta_{\mathrm{v}} \qquad (4)$$

If a displacement transducer is used for the data acquisition, then the power dissipated by the conductor can be calculated from the following equation:

$$P = \pi \times F \times f \times Y_{\mathrm{f}} \times sin\ \theta_{\mathrm{d}} \qquad (5)$$

It should be noted that, in all these cases, the phase angle might have to be corrected due to phase shifting within the transducers as discussed in 5.6.1.

The calculated power can be plotted vs. the antinode amplitude or frequency (see Annex B).

The non-dimensional viscous damping coefficient, $h$, can be calculated by dividing the energy introduced in the conductor $E_{\mathrm{diss}}$ ($=P/f$) by the total kinetic energy of the conductor $E_{\mathrm{kin}}$.

$$h = \frac{1}{4\pi} \frac{E_{\text{diss}}}{E_{\text{kin}}} \tag{6}$$

$E_{\text{kin}}$ is given by the formula:

$$E_{\text{kin}} = \frac{1}{4} mL\omega^2 \; Y_{\text{o}}^2 \tag{7}$$

The power method is simple and requires a limited number of measurement points. However, all the extraneous dissipation is part of the total calculation of the conductor self-damping and special care must, therefore, be devoted to reduce all these extraneous loss sources or to account for them. For example, it is comparatively easy to determine the total amount of vibration energy dissipation in the span, because it is equal to the total amount of energy introduced into the system. This would be quite sufficient for determining the self-damping of the conductor if all the loops of the span had equal energy dissipation. Unfortunately, the loops at the ends of the span and at the shaker connection behave differently from the rest of the span, having an energy dissipation that can be much higher than that of all of the rest of the span.

The end losses can be determined by comparing the power inputs for two spans of different lengths identically terminated. Where it is not convenient to change the span length, it is necessary to minimize these losses or to use the ISWR method.

### 8.3 ISWR Method

The ISWR method determines the power dissipation characteristics of a conductor by the measurement of nodal and antinodal amplitudes on the span at each tunable harmonic.

To understand the principle involved in this method, it is necessary to trace the waves leaving the vibration shaker as they are reflected at the span ends.

For this argument, we may assume that the shaker is attached near one of the span terminations. Impulses induced by the shaker will travel to the far end of the span to return as reflected waves.

If no losses are present in the system, the incident and reflected waves are equal. Perfect nodes will be formed where the two waves meet and pass. That is: zero motion will exist at the nodes. The anti-nodes will have an amplitude equal to the sum of the incident and reflected waves. If losses are present in the system, however, motion will appear at the nodes. The amplitude of this motion will be the difference between the incident and the reflected waves. The ratio between nodal amplitude and anti-nodal amplitude is indicative of the dissipation within the system. Where low span losses are present, the very fine measurements, necessary for determining nodal amplitude, can be a problem.

The ISWR testing procedure is as follows:

- Establish span resonance beginning at the first tunable harmonic within the prescribed frequency range (minimum of ten loops).
- Measure and record the vibration frequency
- Locate a free antinode and an adjacent node.
- Adjust the antinodal amplitude to the prescribed level and record this value.
- Measure and record the nodal amplitude.
- Measure and record the free loop length.
- Measure node and antinode amplitudes in a second location.
- Proceed to the next tunable harmonic frequency.

- Continue this procedure until the upper end of the required frequency range has been reached.

Following the acquisition of data, the total power dissipated by the conductor can be calculated from the following equation:

$$P = \sqrt{T \times m} \times \frac{V_{\mathrm{n}}^{2}}{2} \times \left( \frac{a_{\mathrm{n}}}{Y_{\mathrm{n}}} \right) \tag{8}$$

where

$\sqrt{T \times m}$ is the wave or characteristic impedance (at high frequencies this may be modified due to the effect of the stiffness of the conductor).

$V_{\mathrm{n}} = \omega Y_{\mathrm{n}}$ is the vibration velocity at the $\mathrm{n}^{\mathrm{th}}$ antinode

$S_{\mathrm{n}} = \frac{a_{\mathrm{n}}}{Y_{\mathrm{n}}}$ is the inverse standing wave ratio ISWR at the $\mathrm{n}^{\mathrm{th}}$ loop.

Performing two measurements in two different loops j and k, the power dissipated by the conductor section between these loops will be:

$$P = P_{\mathrm{k}} - P_{\mathrm{j}} \tag{9}$$

And the power dissipated per unit length $P_{\mathrm{c}}$ will be:

$$P_{\mathrm{c}} = \frac{P_{\mathrm{k}} - P_{\mathrm{j}}}{n_{\mathrm{kj}} \frac{\lambda}{2}} \tag{10}$$

where $n_{\mathrm{kj}}$ is the number of loops between nodes k and j, and $\lambda$ is the wavelength.

The value of the non-dimensional viscous damping coefficient is given by:

$$h = \frac{S_{\mathrm{k}} - S_{\mathrm{j}}}{\pi \times n_{\mathrm{kj}}} \tag{11}$$

where $S_{\mathrm{k}}$ and $S_{\mathrm{j}}$ are the ISWR respectively at loop k and j.

Ideally, the two nodes should be as far apart as practical to maximize the difference in their amplitudes relative to the measurement error.

The advantage of this method is that the measured dissipation relates to the considered portion of conductor only; therefore, the estimated self-damping value is not affected by the already mentioned influence of span ends and shaker-conductor connection.

The main problems that the method presents are the correct estimation of the node positions and the measurement of the node amplitude of vibration, which can have a very small value on the order of a few micrometers; an error in the measurement of the node vibration amplitude significantly changes the self-damping estimation.

Two methods can be suggested to improve the accuracy of these measurements.

The first considers to measure in many points around one node and to fit the measurements with an interpolating function: in this way, it is not necessary to know exactly the position of the node (to place the transducers) and the minimum of the interpolating function gives the node amplitude.

The second way would be to use a mathematical model well representing the real deflection shape of the vibrating conductor. This would allow reducing the number of transducers (only two around each node).

The calculated power dissipation can be plotted vs. antinode amplitude or frequency (see Annex B).

### 8.4 Decay method

The decay method determines the power dissipation characteristics of a conductor by the measurement of the decay rate of the amplitude of motion of a span following a period of forced vibration at a natural frequency and fixed amplitude. The rate of decay is a function of the system losses. Where low dissipation levels are present, decay times are long.

This method, if correctly employed, can give, in one trial, an estimation of the value of the self-damping at several vibration amplitudes. Moreover, it is very quick and easy, requiring, in its simplest form, just one transducer measuring the decay. However, as in the Power method, all the extraneous dissipation is part of the total calculation of the conductor self–damping. Therefore it is necessary to minimize all these extraneous loss sources or accounting for them. When this is not possible the use of the ISWR method is recommended.

Decay testing can be applied by bringing a test span into steady state resonance and suddenly removing the excitation by the shaker from the conductor. The decay can be affected by the method used to disconnect the driving force as any additional disturbance of the conductor causes other vibration modes to be generated. With proper precautions, the shaker can be disconnected inducing a minimal disturbing impulse into the system.

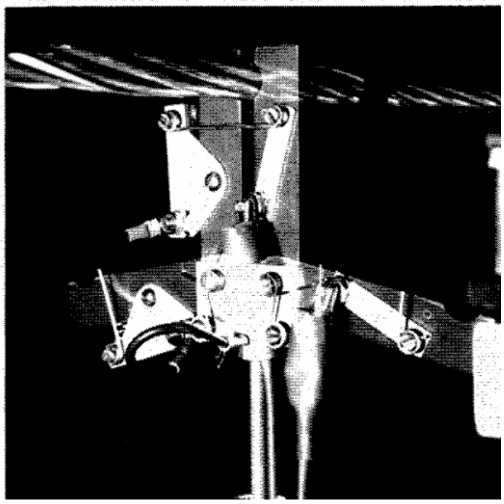
Four methods can be used to terminate forced vibration of a span:

(1) a fusible link to mechanically release a spring-loaded clamp. One example is shown in Figure 9. The shaker is coupled to the span through a link mechanism which is held shut by a length of fuse wire. Opening of the link is accomplished by blowing the fuse using a high current source.
(2) a modal shaker (with a decay relay) which is left attached to the span during the decay phase. The mass of the armature will be active during both the forced vibration and decay phase of the test. The effect will be negligible if the armature mass is small when compared with the total mass of the vibrating span. Nevertheless, friction in the shaker bearings, if any, may contribute to the dissipation of the system. The decrements for the span will reflect all the sources of dissipation, including friction in the shaker.
(3) a very soft connection between the shaker and the conductor under test, which produces a de-coupling between the conductor and the shaker armature. One example is shown in Figure 6.
(4) excitation to the shaker is cut off and a mechanical latch is simultaneously activated to lock the armature and hold it rigid.

The decay test procedure is as follows:

- Establish span resonance beginning at the first tunable harmonic within the frequency range of interest.
- Measure and record the vibration frequency.
- Locate the transducer for vibration level measurement at a mid-span antinode.
- Adjust the antinodal amplitude to be somewhat greater than the prescribed level. This is done to ensure that the test amplitude passes through the prescribed level during the decay.

- Record loop length and loop amplitude.
- Terminate forced vibration, and record the time history of the decay. An oscillographic or other waveform recorder may be used for this purpose.
- Proceed to the next tunable harmonic frequency.
- Continue this procedure until the upper end of the frequency range has been reached.



IEC 2195/13

**Figure 9 – Fuse wire system disconnecting a shaker from a test span; this double exposure shows the mechanism both closed and open.**

Decay rate is recorded and expressed in terms of logarithmic decrement which is basically the natural logarithm of the amplitude ratio of two successive cycles of vibration.

Based on the acquisition of data, the logarithmic decrement can be calculated by the following equation:

$$\delta = \frac{1}{n_\mathrm{c}} ln \frac{Y_\mathrm{a}}{Y_\mathrm{z}} \qquad (12)$$

where

$\delta$ = logarithmic decrement
$n_\mathrm{c}$ = number of vibration cycles between the two cycles considered
$Y_\mathrm{a}$ = single antinode amplitude of the first cycle considered
$Y_\mathrm{z}$ = single antinode amplitude of the last cycle considered

The power P dissipated by the conductor can be determined from the following equation:

$$P \ = \ \frac{1}{2} \times f \times m \times V_{\partial}^{2} \times L \times \delta \qquad (13)$$

where $V_\mathrm{a}$ is antinode velocity at the initial constant antinode amplitude.

If a lightly damped system (h<<1) is left free to vibrate from a forced resonance condition, it undergoes a transient decay of motion that looks like Figure 10.

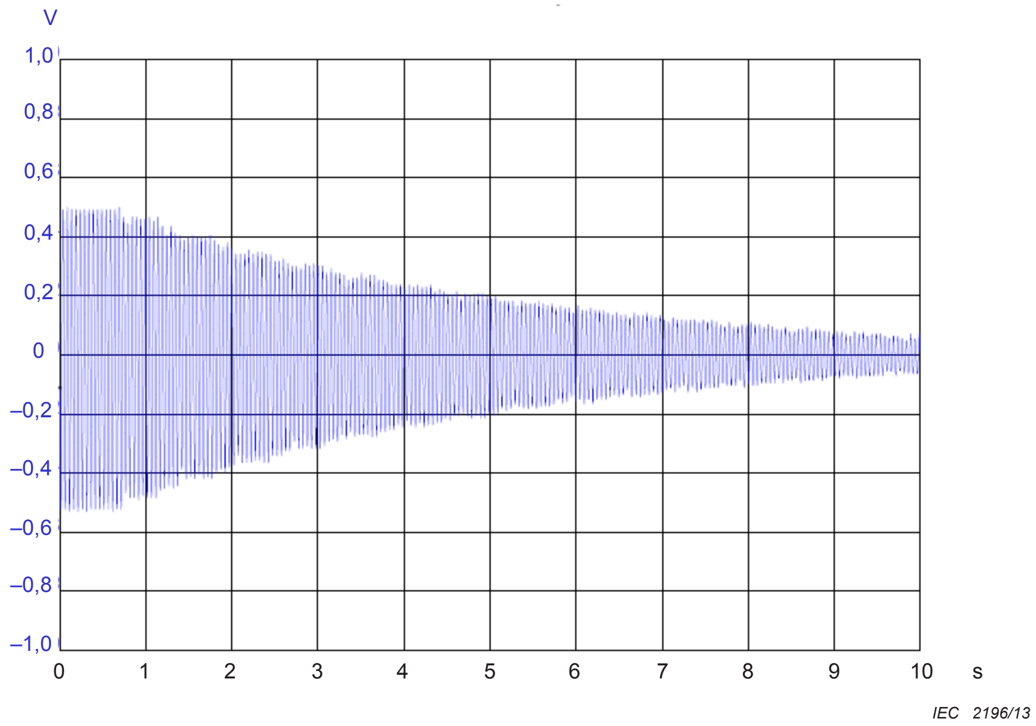


**Figure 10 – A decay trace**

The nondimensional viscous damping coefficient, $h$, can be calculated as follows:

$$h = \frac{\delta}{2\pi} \tag{14}$$

The decay record may take the form of a series of steps occurring at the fundamental frequency of the test span [3,4]. The particular shape of the steps will depend upon where the vibration is sensed and is more pronounced in highly damped spans. The steps are a result of the wave-like character of span vibration. However, in normal cases, they are very shallow due to the fact that dissipation caused by self-damping is quite small and the phenomenon is easily overlooked especially when relatively slow recording speed is used.

The steps may be removed from consideration, if necessary, by fitting a smooth curve to the envelope of the decay trace, and evaluating the decay of that envelope using Equation (12). Applying that equation to the cycles that were actually recorded leads to very inaccurate results unless $n_\text{c}$ is large enough to cover several of the steps or is exactly an integer multiple of the number of vibration cycles per step. Use of the smooth envelope is recommended.

In some cases, a transfer of energy may occur between the horizontal and vertical response of the span, although the initial conditions imposed vertical excitation. When this happens, erratic recordings may be observed. Normally, these occur at certain frequencies that are not prevalent enough to influence the entire program, and these frequencies can be avoided.

To improve the results, it is possible to calculate the energy transferred from the conductor to the shaker during the decay with the same set up already described for the power method. However, this shaker loss is usually one order of magnitude less than that of the conductor.

### 8.5 Comparison between the test methods

Each of the three methods described contains advantages and disadvantages. A comparative summary of some general characteristics of each of the methods is given in Table 1.

**Table 1 – Comparison of laboratory methods**

| General characteristics | ISWR | Power | Decay | Notes |
|---|---|---|---|---|
| test span with unknown end losses | required | not recommended | not recommended | end losses to be minimized in all cases |
| low self-damping conductors | applicable | applicable | applicable | shield wires, ADSS, OPGW |
| high self-damping conductors | Not applicable to conductors that may have a gap | preferable | applicable | special conductors and low conductor tensions |
| Estimated testing time per sample | 36 h | 24 h | 12 h | based on three tensions, three vibration levels and > 10 frequencies |
| Main advantage | Insensitive to end span and drive point losses | simple data collection and analysis | wide range of testing amplitudes in one trial | |
| Main disadvantage | difficult to measure node amplitudes | possible errors due to end and drive point losses | possible errors due to end and drive point losses | |

Although widely accepted, the ISWR and Power Method are considered costly to equip and tedious to perform. The decay method is intuitively easy to understand, relatively easy to perform, and requires minimal instrumentation. When damping is low, the decay test has good accuracy and resolution while both the power method and the ISWR method suffer reduced accuracy, therefore, the decay test may be a suitable complement to these methods. However, when conductor damping is low the relative effect of other damping sources is larger and therefore the ISWR method may be considered advantageous.

## 8.6 Data presentation

It is customary to fit self-damping data to empirical equations that are thought to model the self-damping phenomenon. This is done to facilitate energy balance calculations and to provide a basis for extrapolating the measurements beyond the ranges covered in the laboratory tests. Ability to extrapolate is important since limits on measurement accuracy effectively prevent obtaining useable data at the lower vibration frequencies, yet these may be the frequencies where greatest fatigue stresses occur.

Data measured in the laboratory span are generally expressed empirically through a power law:

$$\frac{P}{L} = k\frac{Y_0^l f^m}{T^n} \tag{15}$$

in which $P/L$ describes the power per unit length dissipated by the conductor, $k$ is a factor of proportionality, $Y_0$ is the antinode amplitude of vibration, $f$ is the frequency of vibration, while $l$, $m$ and $n$ are the amplitude, frequency and tension exponents, respectively. Using the above empirical rule, self-damping determined in laboratory spans could be extrapolated to actual much longer spans.

The damping properties of some conductors, such as ADSS, gap conductors, etc. cannot be expressed by the above formula and require other interpolating functions to be defined as the best fit of the measurement data.

Table 2 (from CIGRE 22.11 TF1 (1998)) summarizes the exponents obtained by a number of investigators for Equation (15), together with the method of measurement used, the test span length, span end conditions and number of conductors and tensions tested.

**Table 2 – Comparison of Conductor Self-damping Empirical Parameters**

| **Investigations** | **l** | **m** | **n** | **Method** | **End Conditions** | **Span length** (m) | **Number of conductors** × **number of tensions** |
|---|---|---|---|---|---|---|---|
| Tompkins et al. (1956) | 2,3 to 2,6 | 5,0 to 6,0 | 1,9 (1) | ISWR | N.A. | 36 | 1 × 2 |
| Claren & Diana (1969b) | 2,0 | 4,0 | 2,5; 3,0;1,5 | PT | M.B. | 46 | 3 × 3 |
| Seppä (1971), Noiseux (1991) | 2,5 | 5,75 | 2,8 | ISWR | N.A. | 36 | 1 × 8 |
| Rawlins (1983) | 2,2 | 5,4 | | ISWR | N.A. | 36 | 1 × 1 |
| Lab. A (CIGRE 22.01 1989) | 2,0 | 4,0 | | PT | M.B. | 46 | 1 × 1 |
| Lab. B (CIGRE 22.01 1989) | 2,2 | 5,2 | | PT | P.E. | 30 | 1 × 1 |
| Lab. C (CIGRE 22.01 1989) | 2,44 | 5,5 | | ISWR | N.A. | 36 | 1 × 1 |
| Kraus & Hagedorn (1991) | 2,47 | 5,38 | 2,80 | PT | P.E. | 30 | 1 × ? |
| Noiseux (1991) (2) | 2,44 | 5,63 | 2,76 | ISWR | N.A. | 63 | 7 × 4 |
| Tavano (1988) | 1,9 to 2,3 | 3,8 to 4,2 | | PT | M.B. | 92 | 4 × 1 |
| Möcks & Schmidt (1989) | 2,45 | 5,38 | 2,4 | PT | P.E. | 30 | 16 x 3 |
| Mechanical Laboratory Politecnico di Milano (2000) | 2,43 | 5,5 | 2 | ISWR | P.E. | 46 | 4 × 2 |

ISWR: Inverse Standing Wave Method

PT: Power Method

N.A.: Non applicable

M.B.: Massive block

P.E.: Pivoted Extremity

(1): extrapolated

(2): Data corrected for aerodynamic damping

The power method for conductor self-damping measurements on laboratory test spans with rigidly fixed extremities produces empirical rules with an amplitude exponent close to 2,0 and a frequency exponent close to 4,0, in comparison to about 2,4 to 2,5 and 5,5, respectively, for the ISWR method and PT method with pivoted extremities.

Such differences in the above exponent values, together with those in the $k$ factor of proportionality, may lead to large differences in the predicted self-damping values. It thus appears that, the major disparities among conductor self-damping values reported by different laboratories are mainly related to end effects.

# Annex A
(normative)

## Recommended test parameters

The values of the tensile load to be used in the test, if not specially required by a particular conductor application, shall be suitably chosen in order to be representative of normal conductor loadings in service.

A minimum of three different tensile loads shall be used, the medium value of which should correspond to the most common conductor loading on the line.

For example, the following loadings suggested by IEEE Std. 563-1978, expressed as percentages of the conductor rated strength RTS can be used 15 (17,5), 20 (22,5), 25 (27,5). The values in brackets are optional.

During the test, the variation of the conductor tensile load shall not exceed ± 3 %.

To ensure tension stability during the tests, testing should be performed in an area where the ambient temperature does not vary more than 0,2 °C/h. If the conductor temperature changes more than 1 °C, adjustment of the conductor tension is necessary.

A minimum of three different antinode double amplitudes for each loop length shall be tested and the values (in millimetres) should be between 25/f and 150/f according to IEEE Std. 563-1978. Alternatively, a minimum of three antinode velocities should be used in the range 100 to 300 mm/s (peak values) as prescribed by IEEE Std. 664-1993. The two ranges are not equivalent.

A minimum of ten different tunable vibration modes shall be tested. Vibration modes should correspond to those associated with frequencies that are generated in the wind velocity range of 1 to 7 m/s on the conductor under test. However, some difficulties may arise for the measurements of the power dissipated at low frequencies due to the long loop lengths associated. A minimum of ten loops is considered necessary to obtain suitable measurements on normal conductors.

The relationship between frequency, wind velocity and conductor diameter is as follows

$$f = 0{,}185 \times \frac{V}{D} \qquad \text{(A.1)}$$

It is recommended that the loop lengths chosen are common to all the tensile loads used. It is also recommended that, within the previously suggested range values, the antinode vibration amplitudes or velocities be the same to all the loop lengths used.

# Annex B
(informative)

## Reporting recommendations

The reporting of test results should be as complete as possible to aid repeatability of the tests. Table 1 of IEEE Std. 563-1978 is an example of a typical table of results. Additional information such as test span description, characteristics of the measurement devices, method(s) and specific testing procedures used, ambient temperature during testing and a description of the conductor under test should be reported. In more details:

- Together with the usual conductor data (manufacturer, year of fabrication, stranding, weight per unit length, RTS), information should be supplied on the type of lubricant or grease applied to it, if any. Moreover, the previous history of the conductor, i.e. if new ex-factory or unused from the store or taken from the line, should be stated. If the specimen is taken from the line, the tensile loads to which it has been subjected and the period of time during which it has been in service should be stated.

  The test span arrangement should be briefly described and shown in a sketch similar to Figure 1. The free span length L and the position of the shaker in the span should be indicated.

  The methods used to assess that no energy was transferred from the conductor free length to span end terminations and to minimize the conductor looseness should be clearly indicated. Otherwise, the methods used to measure such an energy should be clearly stated.
- The method used to correct data for aerodynamic damping should be clearly indicated if this operation has been performed

Moreover information should be provided for:

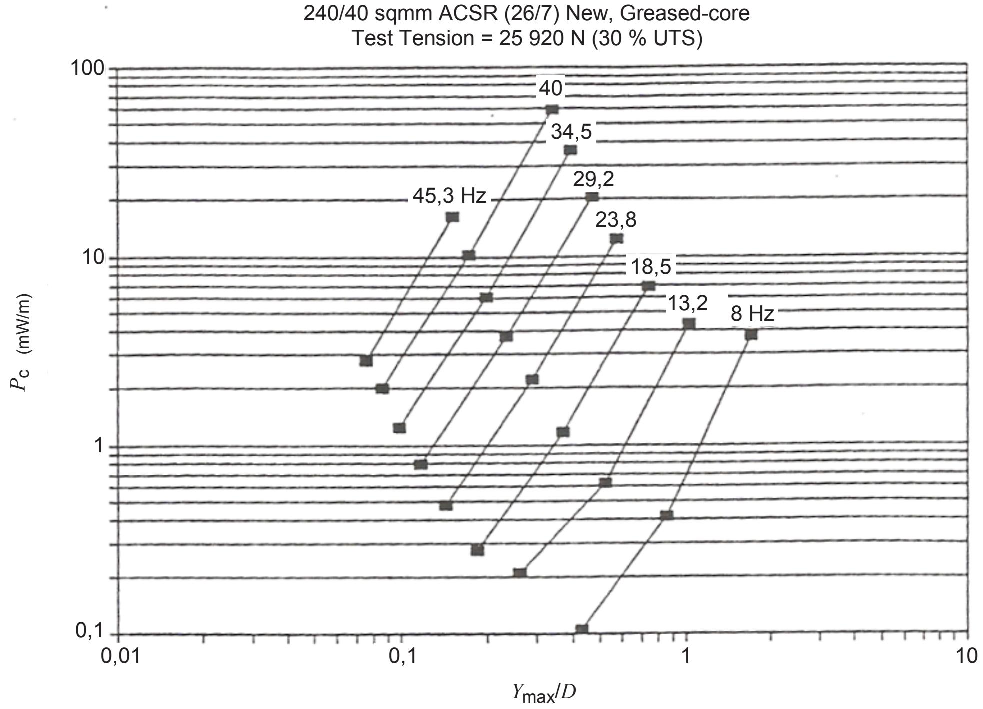
- The accuracy of the tensile load measuring methods.
- Tensile load variations during the test.
- The type of shaker used and the type of mechanical connections between the shaker and the conductor.
- The method used to drive the conductor to vibrate at resonance.
- The method used to assess resonance conditions.
- The parameters that are measured to obtain the power dissipated and the accuracy of the measurements.

IEEE Std. 563-1978 recommends that the measurement results be presented in diagrams showing the power dissipated per conductor unit length, as a function of the ratio of the antinode displacement amplitude $Y_0$ to conductor diameter, for each loop length $\lambda/2$ and corresponding frequency $f$ and tensile load $T$. In the same diagram, the data referring to the different loop lengths and frequencies can be shown provided different symbols are used. It is preferable to present measurement results in different diagrams for each tensile load, unless otherwise required for specific comparison purposes.

Diagrams should clearly show, for each value of $T$, $\lambda/2$, $f$, $Y_0$, all the measured values of $P_c$. The units shall be as indicated in the list of symbols.

An example of these diagrams is given in Figure B.1.

It may be also useful to present the results as a plot of conductor velocity at the drive point against force per unit length for different frequencies and associated loop lengths, for each tension. This presentation allows, by simple calculation, the determination of the power dissipated, the conductor amplitude at the drive point, and the mechanical impedance of the conductor that is the ratio of the force to the conductor velocity, for a wide variety of conditions.



IEC 2197/13

**Figure B.1 – Example of conductor power dissipation characteristics**

Some investigators use to present the results as a family of curves of the power dissipated versus vibration frequency for each vibration amplitude or velocity and for each conductor tension as shown in Figure B.2.

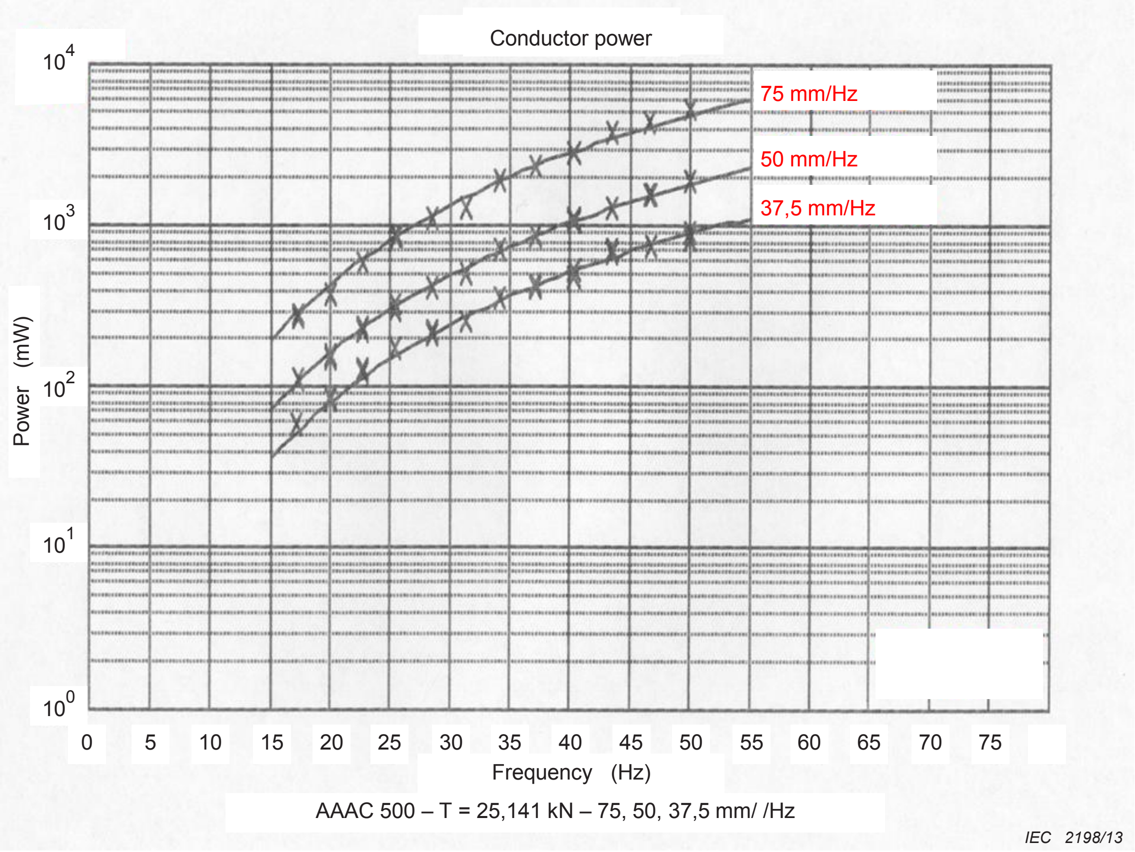


Figure B.2 – Example of conductor power dissipation characteristics

# Annex C
(informative)

## Correction for aerodynamic damping

In order to get the net power dissipated structurally within the conductor, it is necessary to correct the total power measured over the test span for the aerodynamic damping generated by the conductor vibrating in still air. With $P_{\text{net}}$ representing the net structural power loss per unit conductor length, $P_{\text{meas}}$ the measured power loss per unit length and $P_{\text{aero}}$ the power loss per unit length due to aerodynamic damping, this may be done using the following expressions:

$$P_{\text{net}} = P_{\text{meas}} - P_{\text{aero}} \tag{C.1}$$

where

$$P_{\text{aero}} = \pi^2 \times \rho \times f^3 \times x^2 \times d^4 \times \delta_r \tag{C.2}$$

$\rho$ = air density (= 1,205 kg/m$^3$ at 20 °C and 1 atm.)

$f$ = vibration frequency

$x$ = $Y_0/d$

$Y_o$ = free loop single antinode amplitude

$d$ = conductor diameter

and

$$\delta_r = A \times \delta_{\text{st}} + B \times x + C \times x^{D/\sqrt{x}} + E \tag{C.3}$$

where

$$\delta_{\text{st}} = 11{,}137/\sqrt{\beta} \tag{C.4}$$

$\beta$ = Stokes' number (= $d^2 \times f/\upsilon$)

$\upsilon$ = kinematic viscosity of air (= 15,11 × 10$^{-6}$ m$^2$/s at 20 °C and 1 atm.)

The values of the best fit coefficients $A$, $B$, $C$, $D$ and $E$ together with the applicable range of $x$ and $\beta$ are shown Table C.1 for a smooth cylinder as well as for stranded conductors as a function of the number of strands in the outer layer. These coefficients are applicable for sine-loop motion as displayed in actual conductor vibrations.

For 6-strand models vibrating in sine-loops, the formula for $\delta_r$ is:

$$\delta_r = -0{,}55 - 0{,}15\,(\beta - 500)/1\,500 + [3{,}885 + (\beta - 500)/1667] \times x + 1{,}093 \times e^{-2{,}513} \times x \tag{C.5}$$

For smooth body conductors, such as those using trapezoidal strands on their outer layer, it is recommended to use the coefficients applicable to the smooth cylinder in Table C.1.

### Table C.1 – Coefficients to be used with equation C-3

| Stands | A | B | C | D | E | X range | βrange |
|---|---|---|---|---|---|---|---|
| Cylinder | 1,05 | 0,00 | 2,62 | 1,30 | 0,00 | 0 to 0,71 | 340 to 728 |
| 6 | | | | | | 0 to 0,71 | 360 to 781 |
| 10 | 1,00 | 0,37 | 2,91 | 1,25 | 0,06 | 0 to 0,79 | 288 to 626 |
| 12 | 1,10 | 0,66 | 1,70 | 1,20 | 0,00 | 0 to 0,59 | 512 to 1 111 |
| 16 | 1,20 | 0,00 | 2,43 | 1,15 | 0,00 | 0 to 0,69 | 364 to 778 |
| 18* | 1,15 | 0,17 | 2,35 | 1,33 | 0,00 | 0 to 0,63 | 452 to 966 |
| 20 | 1,10 | 0,34 | 2,27 | 1,50 | 0,00 | 0 to 0,56 | 540 to 1 154 |
| 24 | 1,15 | 0,24 | 2,07 | 1,40 | 0,00 | 0 to 0,47 | 650 to 1 594 |
| 27 | 1,40 | 0,26 | 2,47 | 1,40 | 0,00 | 0 to 0,43 | 913 to 1 956 |

* Entries in the 18 strand case are interpolated.

# Annex D
(informative)

## Correction of phase shift between transducers

Using transducers having a different working principle, for example a piezoelectric accelerometer and a strain gauge load cell, it is possible to have a phase shift between the two signals due to the different response time of the two transducers.

This phase shift can be measured mounting the transducers on a shaker table and fixing a small mass on the force transducer. The transducers should be shaken at all proposed test frequencies, and at approximately the amplitudes chosen for the conductor test.

The phase shift angle between the force and acceleration (or displacement) signals, due to the different principle of functioning of the two devices, increases linearly with the frequency. This phase shift angle should be recorded for each tunable frequency and subtracted from the phase angle measured, at the same frequency, during the self-damping measurements.

To simplify this procedure, it is suggested to measure the phase angle $\alpha$ (rad) between the signals of the two transducer at a frequency $f$ (Hz) and then calculate the time shift $t_s$ (s) between the transducer signals by the following formula:

$$t_s = \frac{\alpha}{2\pi \times f} \qquad \text{(D.1)}$$

Considering that $t_s$ is constant, the phase shift angle $\alpha$ can be calculated for any other vibration frequency by the same formula.

For better precision, the time shift $t_s$ should be determined for three or more different frequencies and the average value used as indicated above.

# Bibliography

[1] Tompkins, J.S., L.L. Merrill and B.L. Jones. October 1956. “Quantitative Relationships in Conductor Vibration Damping”. AIEE Transactions, Part III (Power Apparatus and Systems) vol.75, pp. 879-84.

[2] Rawlins C.B., 1958. “Recent Developments in Conductor Vibration Research”. Alcoa, Technical paper No. 13.

[3] Slethei, T.O. and Huse, J. June 1965. “Conductor Vibration – Theoretical and Experimental Investigations on a laboratory Test Span.” Proceeding IEEE (London), vol.112, pp. 1173-1179.

[4] Hard A. R. and R. D. Holben. February 1967 “Application of the vibration decay test to transmission line conductors” AIEE Transactions (Power Apparatus and Systems) vol. PAS-86 no.2 , pp. 189-199.

[5] Claren, R., and G. Diana. 1969. “Mathematical Analysis of Transmission Line Vibration.”IEEE Trans Power Appar. Syst., Vol. PAS-88, pp. 1741-71.

[6] Seppä, T. 1971. “Self-damping measurements and energy balance of ACSR Drake”. IEEE Winter Power Meeting. New York. Paper No 71-CP-161-PWR, 8 pp.

[7] Di Giacomo G: 1972 “Internal damping characteristics of Zebra conductor”. ENEL DSR-CREI Report L6/73-27.

[8] CIGRE. 1979. “Guide on conductor self-damping measurements.” Electra Vol. 62 (identical to IEEE 563-1978 Standard).

[9] Doocy et al, 1979. “Wind Induced Conductor Motion”. Section 3.3 EPRI Transmission Line Reference Book, Electrical Power Research Institute, Palo Alto.

[10] Rawlins C.B., July 1983. “Notes on the measurements of conductor self-damping”. Alcoa, Technical report No 93-83-4.

[11] CIGRE, May 1985. “Guide for endurance tests of conductors inside clamps.” Electra, No 100. pp. 77-86.

[12] Noiseux D.U., Houle S., and Beauchemin R. December 1986 « Study of effective aeolian wind power imparted to single conductor spans » Canadian Electrical Association (CEA) Research Report 146 T 328.

[13] Tavano, F. 1988. “Results of self-damping measurements on conductor for overhead lines and on earth wires with optical fibres”. CIGRE Report SC22-88(WG11)18.

[14] CIGRE SC22 WG01. May 1989. “Report on Aeolian Vibration.” Electra Vol. 124, pp. 40-77.

[15] Möcks, L. and Schmidt J. 1989. “Survey on measurements of mechanical self-damping of ACSR conductors” CIGRESC22-89 (WG-11)TF1-2.

[16] Hardy C. June 1990 “Analysis of self-damping characteristics of stranded cables in transverse vibration” CSME Mechanical Engineering Forum Toronto.

[17] Tavano, F. 1991. “Collection of experimental data on conductor self-damping”. CIGRE Report SC22-91(WG11-TF1)7.

[18] Kraus, M. and Hagedorn, P. July 1991 “Aeolian vibration: wind energy input evaluated from measurements on an energized transmission line” IEEE Trans Power Del, Vol. 6, Iss. 3, pp.1264-1270.

[19] Claren, R. Diana, G. Tavano, F. 8 September 1991 “Proposal for calculating, on the basis of experimental results, the conductor self-damping. CIGRESC22-91 (WG-11 – TF1).

[20] Noiseux D. 1992 “Similarity law of the internal damping of stranded cables in transverse vibration” IEEE Trans Power Del, Vol. 7, No. 3, pp.1574-1581.

[21] Hardy C. A. Leblond, 1993. “Comparison of Conductor Self-Damping Measurements” CIGRE SC22-93 (WG-11)88.

[22] Tavano, F. et al. August 1994. “Conductor Self-Damping”. CIGRE Report SC22-94 (WG11)-126.

[23] A. Leblond, L. Cloutier, C. Hardy & L. Cheng, 1995, "A Model on Self-Damping of Stranded Cables in Random Transverse Vibrations", Canadian Acoustics, 23(3), 1995, pp. 31-32.

[24] C. Hardy, A. Leblond, L. Cloutier & S. Goudreau, 1995, "Review of Models on Self-Damping of Stranded Cables in Transverse Vibrations", Proc. of the International Symposium on Cable Dynamics, Liege, Belgium, October 19-21, pp. 61-68.

[25] Papailiou, K.O. 1997. “On the Bending Stiffness of Transmission Line Conductors”. IEEE Trans Power Del, Vol. 12, No. 4, pp.1576-1588.

[26] Leblond & C. Hardy, 1997, "Extended Similarity Laws of Self-Damping for Multilayered Stranded Cables in Transverse Vibrations", Comptes rendus du 16ième Congrès canadien de mécanique appliquée, Université Laval, Québec, 1-5 juin, pp. 155-156.

[27] S. Goudreau, F. Charette, C. Hardy & L. Cloutier, 1998, "Bending Energy Dissipation of Simplified Single-Layer Stranded Cable", J. of Engineering Mechanics, ASCE, August, pp. 811-817.

[28] Consonni, E., P.Marelli, M. Falco, A. Cigada and M. Vanali. November 1998. “All Dielectric Self -Supporting Cables: mechanical features and aeolian behaviour.” Proc. of the Int. Wire and Cable Symposium (IWCS). Philadelphia.

[29] CIGRE SC22 WG11 TF1. December 1998. “Modelling of Aeolian Vibrations of Single Conductors: Assessment of the Technology.” *Electra* Vol. 181, pp. 53-69.

[30] C. B. Rawlins, “Measurements of Fluid-Dynamic Damping of Stranded Cable Models at Low Oscillation Amplitudes”, *Proceedings,* 1998 ASME Fluid Engineering Division Summer Meeting, June 21-25, 1998, Washington DC.

[31] C.B. Rawlins, Addendum to above paper.

[32] Hardy C., A. Leblond, S. Goudreau and L. Cloutier. 1999. “Application of Contact Mechanics to Cable Self-Damping.” Third International Symposium on Cable Dynamics. Trondheim (Norway), August 16-18. pp. 1-6.

[33] Diana, G, Falco, M. Cigada, A. and Manenti A. January 2000. “On the measurement of over head transmission lines conductor self-damping.” IEEE Transactions on Power Delivery Vol. 15, No.1, pp. 285-292.

[34] C. Hardy & A. Leblond, 15-18 September 2003, “On the Dynamic Flexural Rigidity of Taut Stranded Cables”, Proceedings of the Fifth International Symposium on Cable Dynamics, Santa Margherita Ligure (Italy), pp.45-52.

[35] Dastous, J. B. January 2005. “Non linear Finite-Element Analysis of Stranded Conductors with Variable Bending Stiffness using the Tangent Stiffness Method.” IEEE Transactions on Power Delivery Vol. 20, No. 1, pp 328-338.

[36] A. Leblond & C. Hardy, 19-22 September 2005, “Assessment of the Fretting-Fatigue-Inducing Stresses within Vibrating Stranded Conductors in the Vicinity of Clamps”, Proceedings of the Sixth International Symposium on Cable Dynamics, Charleston, S.C., U.S.A.

[37] EPRI Transmission Line Reference Book, 2006 “Wind-Induced Conductor Motions” Chapter 2. EPRI, Palo Alto, CA 1012317.

[38] C. B. Rawlins, 2008, “Review of selected self-damping data using the flexural hysteresis model. Power Point presentation, CIGRE SC22-08 (WG-11) Paris.

[39] C. B. Rawlins, 2009, “Flexural self-damping in overhead electrical transmission conductors” Journal of Sound and Vibration.323 (2009) 232-256.

[41] CIGRE SC22 WG B2.25, 2011 “State of the art for testing self-damping characteristics of stranded conductors for overhead lines. TB 482, December 2011[1]

---

[1] To be published.

# British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

## About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards-based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

## Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

## Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

## Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

**PLUS** is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email bsmusales@bsigroup.com.

## Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

## Copyright

All the data, software and documentation set out in all British Standards and other BSI publications are the property of and copyrighted by BSI, or some person or entity that owns copyright in the information used (such as the international standardization bodies) and has formally licensed such information to BSI for commercial publication and use. Except as permitted under the Copyright, Designs and Patents Act 1988 no extract may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, photocopying, recording or otherwise – without prior written permission from BSI. Details and advice can be obtained from the Copyright & Licensing Department.

## Useful Contacts:

**Customer Services**
**Tel:** +44 845 086 9001
**Email (orders):** orders@bsigroup.com
**Email (enquiries):** cservices@bsigroup.com

**Subscriptions**
**Tel:** +44 845 086 9001
**Email:** subscriptions@bsigroup.com

**Knowledge Centre**
**Tel:** +44 20 8996 7004
**Email:** knowledgecentre@bsigroup.com

**Copyright & Licensing**
**Tel:** +44 20 8996 7070
**Email:** copyright@bsigroup.com

**BSI Group Headquarters**

389 Chiswick High Road London W4 4AL UK

bsi.

...making excellence a habit.™