VETOR

Impact of Vibrations on Aluminum Conductor Fatigue: A Novel Testing Approach☆

Impacto das Vibrações na Fadiga de Condutores de Alumínio: Uma Nova Abordagem de Teste

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Abstract

In transmission lines, wind-induced vibrations, like high-frequency wind vibrations and low-frequency galloping phenomenon, can cause fatigue damage and failure, particularly in aluminum conductors, which have greater flexibility. Wind loads are variable forces applied by the wind to structures, including conductors. These dynamic wind loads vary with weather and altitude where the conductors are located, causing mechanical dissipation energy due to wire friction, particularly in contact zones. To ensure stability and safety, these loads and the damping effect must be taken into account when planning electrical transmission systems. The aim of this study is to investigate the impact of wind loads on the conductor's self-damping characteristics using a new approach to self-damping testing. Indeed, a self-damping test was carried out at the University of Brasilia's fatigue laboratory on 838 MCM AAAC 1120. The test bench was operated at frequencies ranging from 15.25 to 35.55 Hz, with the catenary parameter H/w = 2143 m, representing the ratio between the initial horizontal tensile load (H) and the conductor weight (w) per unit length. The power dissipated per unit length was calculated using the power method. It uses a methodology that allows the dissipation of mechanical energy to be measured accurately. The analysis revealed that higher frequencies lead to greater energy dissipation. Higher normalized amplitude with respect to the conductor diameter (Y/D ratio) lead to greater dissipation at the same frequency. The increase follows a power-law behavior, which is typical of vibration systems where the dissipated energy depends on frequency and amplitude.

Keywords

Aluminium Alloy Conductor • Transmission line • Self-damping • Eolian – vibration • Fatigue

Resumo

Nas linhas de transmissão, as vibrações induzidas pelo vento, como vibrações eólicas de alta frequência e o fenômeno de galope de baixa frequência, podem causar danos por fadiga e falhas, particularmente em condutores de alumínio, que têm maior flexibilidade. As cargas de vento são forças variáveis aplicadas pelo vento às estruturas, incluindo os condutores. Essas cargas dinâmicas variam de acordo com o clima e a altitude onde os condutores estão localizados, causando dissipação de energia mecânica devido ao atrito dos fios, especialmente nas zonas de

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contato. Para garantir estabilidade e segurança, essas cargas e o efeito de amortecimento devem ser considerados no planejamento dos sistemas de transmissão elétrica. O objetivo deste estudo é investigar o impacto das cargas de vento nas características de autoamortecimento do condutor, utilizando uma nova abordagem para testes de autoamortecimento. De fato, um teste de autoamortecimento foi realizado no laboratório de fadiga da Universidade de Brasília, utilizando o condutor 838 MCM, CAL 1120. A bancada experimental foi operada em frequências variando de 15,25 a 35,55 Hz, com o parâmetro de catenária H/w = 2143 m, representando a razão entre a carga horizontal inicial (H) e o peso do condutor (w) por unidade de comprimento. A potência dissipada por unidade de comprimento foi calculada pelo método da potência, Ele utiliza uma metodologia que permite medir com precisão a dissipação de energia mecânica. A análise revelou que as frequências mais altas levam a uma maior dissipação de energia. Amplitudes normalizadas mais elevadas em relação ao diâmetro do condutor (Y/D) resultam em maior dissipação na mesma frequência. Esse aumento segue um comportamento de lei de potência, típico de sistemas vibratórios onde a energia dissipada depende da frequência e da amplitude.

Palavras-chave

Condutor Alumínio Liga • Linha de Transmissão • Autoamortecimento • Vibração Eólica • Fadiga

1 Introduction

The integrity of overhead conductors in power transmission systems is essential to ensure the reliability and safety of electrical distribution worldwide. Overhead conductors in transmission lines are often exposed to load conditions including wind, and their own weight, resulting in fatigue load stresses over time. This continuous loading can lead to fatigue damage, particularly when combined with wind-induced vibration and static loads such as tensile stress and the conductor's own weight, which can result in fatigue wire breaks [1-3].

This process is particularly relevant for assessing contact wear damage in multi-strand copper conductors, where the complexity of contact interactions and dynamic loads increase the risk of structural degradation [4]. Studies show that the phenomenon of contact fatigue is one of the main causes of overhead conductor failure, particularly in regions close to suspension clamps, where high levels of tension, combined with low relative displacements in the contact zones, promote a characteristic damage process [5-7].

Indeed, in the context of electrical engineering and power transmission, the conductors play a fundamental role in the efficient and safe conduction of electricity [8]. Over the last 130 years, overhead conductors have begun to be used in transmission lines. Today, the growth in demand for energy is becoming increasingly important, especially in developing countries, where the demand for electricity has increased by more than 2.4% per year [9-11].

The Brazilian transmission system, with an average of 20 years of operation, faces challenges such as the competitiveness of the energy sector, the lack of resources for new investments and the aging of the system [12]. In order to meet the growing demands of the energy market and also to guarantee the reliability of their predictions, with regard to overhead electrical conductors, which represent an element important in the transmission of electrical energy, there is a great need for reform and studies.

The problem of vortex-induced vibrations (VIV) on cylinders that can move transversely to the fluid flow has been the subject of numerous in-depth studies [13-16]. Several specialized papers deal with this phenomenon in detail, including the works of [17,18]. These studies provide an exhaustive analysis of VIV mechanisms, theoretical models and experimental results, offering a solid basis for understanding and mitigating the effects of VIV on structures exposed to fluid flows.

Conductor vibrations, particularly those induced by vortices (VIV), are a major topic of interest in the context of overhead power lines. When conductors are exposed to wind flows, alternating vortices can form, creating periodic forces that lead to transverse oscillations. These are of practical interest in many areas of engineering, for a number of reasons: especially in the energy sector, where wind turbine blades are also subject to VIV. A better understanding of these vibrations enables their design to be optimized for more efficient and sustainable energy production, as these forces can cause fatigue and long-term damage, reducing the service life of structures.

The process of limiting wear and damage due to wind-induced vibrations is complex. In this work, we study the characteristics of conductor self-damping under the effects of dynamic loads. The work was carried out in accordance with the IEEE and CIGRE standards, using an experimental test rig with a 43 m span. The conductor was fixed by two rigid gramps at either end, where the total power dissipated by the conductor was determined using the power method. Following the work of Ref. [19] and other researchers [20-21], who conducted tests on a laboratory span, we have developed a methodology for determining the self-damping of a conductor subjected to dynamic loads.

Thus, this research provides a solid basis for the development of methodologies to predict and mitigate fatigue damage in overhead conductors, helping to increase the reliability of power transmission lines.

2 Theoretical Basis

2.1 Conductor's vibration

Wind-induced vibrations on overhead conductors are explained by the interaction between fluid (wind) and solid (conductor). This concept of fluid-solid interaction has been in use since the 1920s, when the phenomenon was first observed.

When wind blows perpendicular to the conductor, it creates vortices called Von Karman vortices, which induce periodic vibrations in the conductor. If the frequency of these vibrations matches a natural frequency of the conductor, resonance occurs, amplifying the vibrations. The frequency of vortex detachment depends on wind speed, conductor diameter and the Strouhal number, a constant that describes the behavior of the fluid around the solid.

This vortex detachment frequency can be calculated by Eq. (1), where the resonance caused by this interaction can lead to significant vibrations, potentially dangerous for overhead line conductors:

$$f = \frac{C_s \times v}{D}, \tag{1}$$

where Cs is the Strouhal number (approx. 0.18 - 0.22), D is the conductor diameter, and v is the airflow velocity in the direction perpendicular to the longitudinal axis of the conductor.

2.2 Self-damping measurement method

Conductor self-damping refers to a physical characteristic of the conductor that defines its ability to dissipate energy internally when vibrating. These tests enable us to assess the conductor's ability to dampen internal vibrations, which is essential for understanding its behavior under real-life operating conditions.

In accordance with standard Std 664-1993 prescribed by the Institute of Electrical and Electronics Engineers (IEEE) and CIGRÉ SC22 1979, three main methods are recognized for determining the bending self-damping of conductors: the inverted standing wave ratio (ISWR) method, the power method and the logarithmic decay method. These methods are divided into two main categories, i.e., they are differentiated according to their induced vibration modes, which are generally referred to as "forced vibration" and "free vibration" methods. As stated in Ref. [22] :

- The first forced vibration method is the "Power [test] method", in which the conductor is subjected to resonant vibrations at a number of adjustable 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, the "inverse standing wave ratio [test] method" (ISWR), measures the amplitudes at the antinodes and nodes on the span.
- The free vibration method, known as the "decay [test] method", determines the power dissipation characteristics of a conductor by measuring the rate of decay of the amplitude of a free movement following a forced vibration period.

In accordance with Ref. [23], power dissipation can be plotted as a function of frequency or wind speed using the Strouhal relationship. At least five different loop lengths should be tested, with maximum and minimum values corresponding to the minimum and maximum frequencies generated in a specific wind speed range cited in previous paragraphs for the conductor diameter concerned. Test frequencies must be calculated from the Eq. (2) and must be within the value, using the Maximum and minimum wind's velocity:

$$f \ (Hz) = 50 \times \frac{V}{D}, \tag{2}$$

where:

f: is the Frequency (Hz);

V: is the speed of wind (km/h);

D: is the Conductor's Diameter (mm).

2.3 Self-damping measurement by using Power Method

According to Ref. [23], whose main objective is to describe some of the procedures for determining the dynamic characteristics of vibration dampers and damping systems, as well as quantifying the power dissipation characteristics of vibration dampers by applying an appropriate laboratory test method. As already mentioned in the previous paragraphs, due to the diversity of vibration damper designs, several test methods may be necessary to obtain the required information on dissipation characteristics.

On the other hand, although the ISWR method is potentially very reliable, it is not recommended by many researchers due to measurement difficulties associated with the vibration amplitude of the conductor node, which is very low due to the reduced value of the conductor's self-damping [19]. In comparison with other methods, The Power method is very simple to apply, it was used to determine the conductor's self-damping.

To determine the dissipation characteristics of the damper, the Power method described in Eq. (3) was used. This method involves attaching a small mass rigidly to the conductor clamp and shaking this mass at all the proposed test frequencies and at an amplitude approximately equal to that expected during damper testing.

$$P = \frac{1}{2}\left(F.V_s\right) \times cos\left(\varphi\right), \tag{3}$$

where:

P: is the power dissipated by the damper;

F: is the force measured at the vibrator;

Vs: is the velocity measured at the vibrator and φ: is the phase angle difference between the measured force and velocity signals.

To ensure the verification procedure for transducers used in force and velocity measurement tests, the IEEE standard [23] requires two criteria: the phase angle between force and velocity must be equal to or close to 90 degrees, meaning that force and velocity must be in phase, or nearly so, and the ratio between force and acceleration (F/As) must be constant at all frequencies. This means that, regardless of the frequency at which the system is vibrating, the system's response in terms of acceleration must be proportional to the force applied. This constant ratio indicates that the system's dynamic behavior is predictable and linear across different frequencies. The purpose of this linear behavior (constant ratio) is to guarantee the reliability of the results obtained over the range of test frequencies.

3 Material and experimental setup

This section is structured in three main sections. The first section details the specific characteristics of the conductor, such as its composition, dimensions, and mechanical and electrical properties. The second section presents the experimental configuration of the self-damping test bench, developed in accordance with IEEE standards. It includes the layout of the equipment, the measurement instruments used, and the test conditions applied. The third section describes the experimental methodology in detail, explaining the procedures followed to conduct the tests, the data collection techniques, and the methods of result analysis. This structure aims to provide a comprehensive and precise understanding of the testing process and the parameters evaluated.

3.1 All Aluminum Alloy Conductor (AAAC 1120 / 838 MCM)

The conductor is the only part of the transmission line that carries electrical energy, so electrical conductivity is one of the most important properties in this choice. In the past, copper was used as a conductor because it had excellent electrical conductivity. Due to its exorbitant price on the market, pure aluminum was used as a conductor. However, the latter has a number of shortcomings in terms of mechanical properties, so an improved version, aluminum alloy, was used.

This 838MCM aluminum alloy conductor shown in the Fig. 1, whose specifications/characteristics are shown in Table 1, offers greater resistance to corrosion than most other conductors, which is why it is widely used in coastal areas.

It was developed to meet the need for an economical conductor for overhead applications, where greater mechanical strength is required. In fact, the use of 1120 alloy in the manufacture of conductors for transmission lines is based on its greater mechanical strength than other alloy conductors. Since 1984, in Australia, 1120 aluminum alloy conductors have been used in transmission lines due to their combination of high mechanical strength and creep resistance [24]. Creep resistance is a major concern in alloys as it is a crucial element to ensure the durability and reliability of electrical components. Therefore, in 1978, the Association for Electrical Research was tasked with conducting a research project aimed at comparing the creep performance of alloy 6201 with that of four other aluminum alloys [24]. The objective of this work was to determine which alloy had the best creep resistance properties.

Figure 1: Geometry of the AAAC 1120/838 MCM conductor.

Table 1: Geometric and mechanical characteristics of the AAAC 1120/838 MCM conductor.

Geometric and mechanical Properties	AAAC 838 MCM
Tensile strength (MPa)	249
Mass Linear (kg/km)	1170.9
Wire diameter (mm)	3.825
Number of wires	37
Conductor diameter (mm)	26.78

3.2 Experimental Test bench

In compliance with the CIGRE standard, the self-damping test was carried out on the experimental test bench C of the Laboratory of Fatigue and Structural Integrity of Energy-Conducting Cables - Labcabos - at the University of Brasilia (UnB), where the test span consists of two solid blocks, 43 m apart, as shown in the Fig. 2, on which the conductor to be characterized, tensioned to the required traction load, is held at both ends by two rigid Clamp and a Tension Clamp located in the area of the load cell and the Weight control (Lever arm). The ambient temperature is also controlled at 21°C. This constant temperature ensures homogeneous experimental conditions, essential for reliable results.

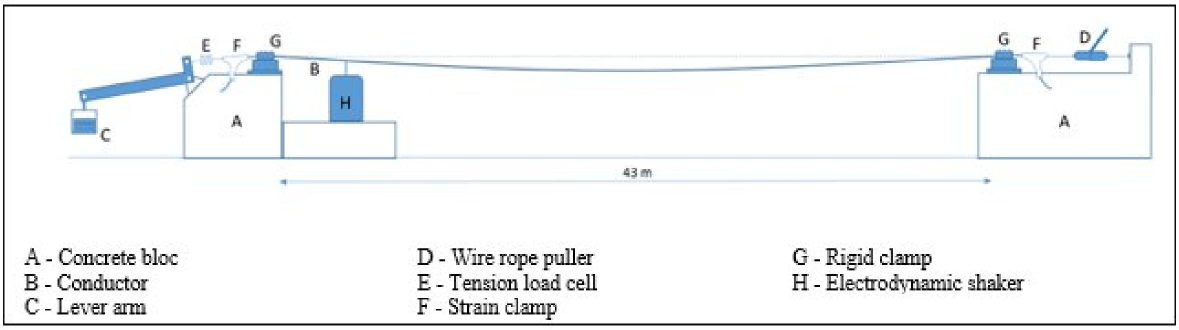

Figure 2: The experimental self-damping test bench.

The use of an electrodynamic exciter in Fig. 3 is to maintain the vibration of a conductor at one of its natural frequencies under steady-state conditions, with control of both amplitude and frequency. An accelerometer on the agitator is used to measure and control the vibrations generated by the agitator. An accelerometer on the conductor is used to measure the vibrations experienced by the cable during laboratory testing and to record conductor vibration levels under different test conditions. The load cell, when mounted on the agitator, is used to measure the force applied by the agitator.

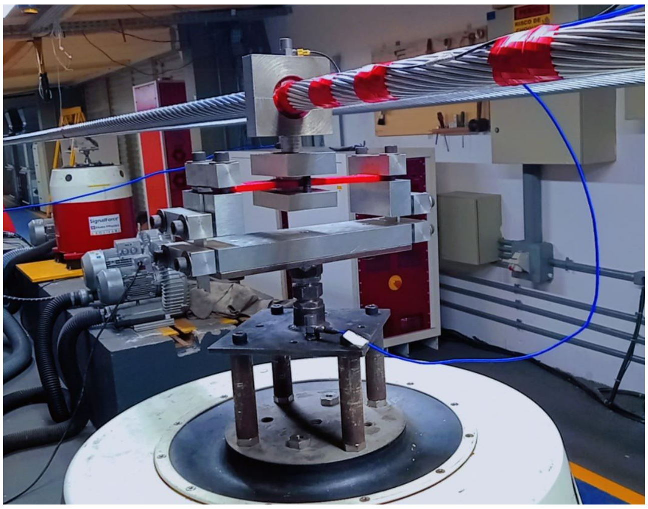

Figure 3: Association of sensors and coupling system with shaker.

The way in which the vibration mode is transmitted from the excitation, device to the conductor results in energy losses that can be considered undesirable because they potentially affect the efficiency of the vibration system. The latter is at the root of changes and distortions in the conductor's vibration modes. To this end, as shown in the Fig. 3, there is a connection between the exciter (a device used to induce vibrations in the conductor) and the conductor accompanied by a coupling system, which allows unwanted losses and signal responses to be generated during vibration.

3.3 Experimental Methodology

In accordance with the Fig. 4 showing the sweep test process realized with 1 mm Peak – to - Peak of displacement amplitude, highlighting how the calculated frequencies are used to control the test and obtain relevant data on the frequency values that will be used to perform the self-damping tests.

It is essential that the tension is high enough to allow the conductor to vibrate naturally at the desired frequency. In other words, the tension must be adjusted in order that the conductor resonates at the specific frequency to be tested. This ensures appropriate test conditions and meaningful results. A minimum of three different antinodal double amplitudes for each loop length should be tested, and the values should lie between the following values.

$$Y_{min} = \frac{25}{f(Hz)}, \tag{4}$$

$$Y_{min} = \frac{150}{f(Hz)}. \tag{5}$$

In accordance with Fig. 4, which shows the sweep test performed using the Shaker Control program, the frequency values were chosen to determine the amplitude values shown in Table 2. It should be noted that the frequency values were chosen in the low-frequency range in order to obtain higher amplitude values and allow the conductor to vibrate naturally at the desired frequencies.

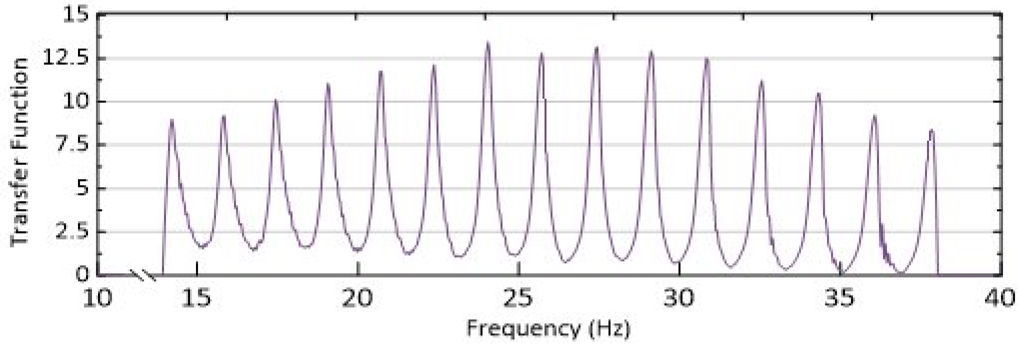

Figure 4: Transfer function of the sweep test with the Frequency range 14 – 36 Hz and 1 mm Peak – to – Peak of displacement amplitude.

Table 2: Amplitude of vibration

Frequency (Hz)	15.25	19.95	24.50	30.50	35.55
Y_{min} (mm)	*1.63*	*1.25*	*1.02*	*0.82*	*0.70*
Y_{Med} (mm)	*5.73*	*4.38*	*3.57*	*2.86*	*2.46*
Y_{Max} (mm)	*9.83*	*7.51*	*6.12*	*4.91*	*4.21*

By vibrating the conductor using these specific values of vibration amplitude and frequency, data were collected from the Shaker Control program. This program provides precise measurements of the velocity, phases and forces exerted on the conductor during vibration. These enable us to determine the power dissipated per unit length of conductor for each frequency. This approach enables us to analyze in detail the dynamic behavior of the conductor and evaluate its self-damping under different vibratory conditions.

4 Results and discussions

The following results are based on experimental data where the conductor was subjected to a forced vibration system at different vibration frequencies. The Fig. 5 shows the power dissipated per unit length for the frequency's modes: 15.25; 19.95; 24.50; 30.50 and 35.55 Hz. For each frequency mode there are five of power dissipation value, making a total of 25 tests carried out at five frequency values and five amplitude values for each frequency. All these tests were carried out to observe the variation in energy dissipation behavior as a function of vibration frequency and amplitude.

Analyzing the results in Fig. 5 and Fig. 6, it was observed that self-damping is more effective at higher frequencies because the system dissipates more energy at this frequency. This, is necessary to understand conductor behavior under wind-induced vibrations or high-frequency dynamic loads. The analysis also revealed that for each frequency, power dissipation increases with normalized displacement (Y/D ratio) and coincides very well with the experiments, as shown in Fig. 5 and Fig. 6. This trend is consistent across all frequencies, implying that higher vibration amplitudes result in greater energy dissipation.

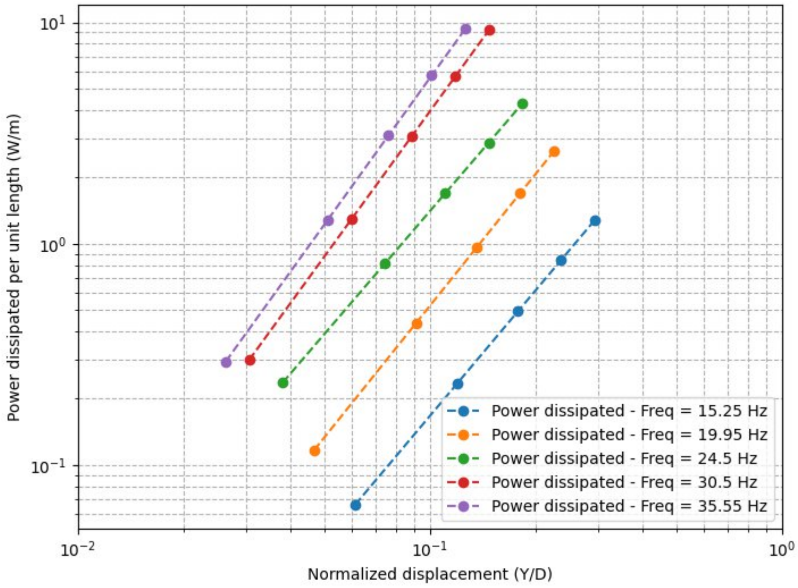

Figure 5: Power dissipated versus Y/D of AAAC 1120/838 MCM Conductor for H/w = 2143 m.

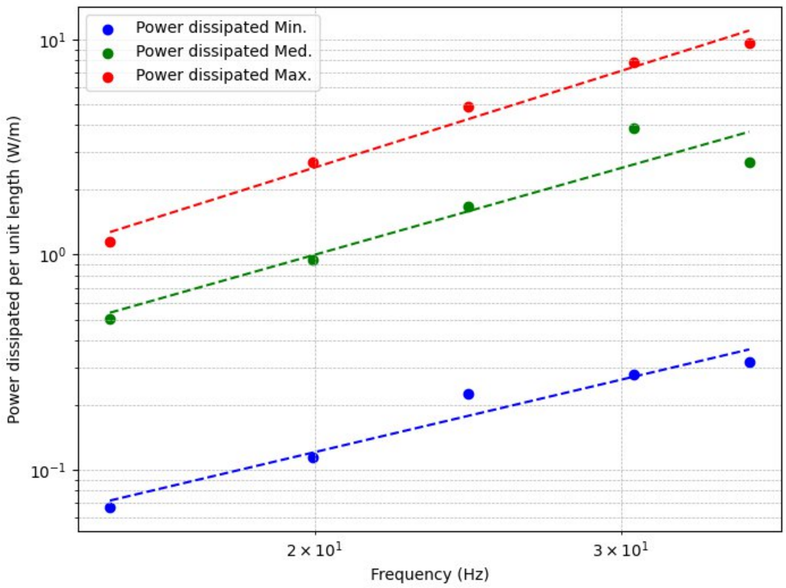

Figure 6: Power dissipated max, med. and min. versus frequency.

Figure 7 shows that the conductor was subjected to two different vibration amplitudes. The conductor was vibrated at each frequency value with an amplitude of 1 mm and 0.70 mm peak-to-peak. Analysis revealed that higher frequencies and greater displacements lead to greater energy dissipated. The relationship between power dissipation and frequency appears to be linear. This linearity shows that energy dissipation follows a power law with the frequency, which is common in dynamic systems.

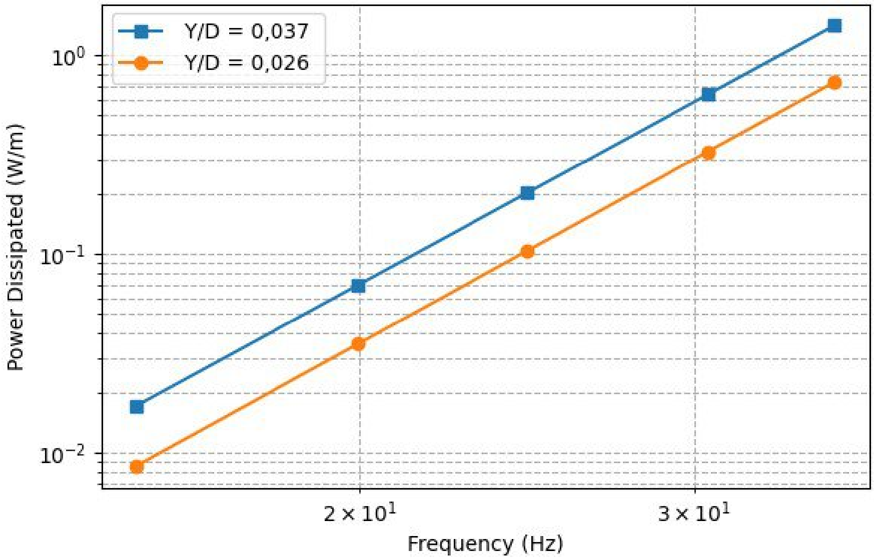

Figure 7: Power dissipated versus frequency of AAAC 1120 / 838 MCM with H/w = 2143 m.

5 Conclusions

Based on the results of the self-damping test carried out with the AAAC 1120 / 838 MCM conductor, which was subjected to the parameter value H/w = 2143 m, which represents the stretching load proposed by the CIGRE organization against fatigue of conductors due to wind vibrations. Where H represents the horizontal tensile load of the power line and w the weight per unit length of the conductor. Based on the analysis results, several important dynamic information related to the self-damping behavior of the conductor was observed, focusing particularly on how frequency and normalized amplitude Y/D (ratio of peak-to-peak displacement amplitude of the anti-node to the diameter of the conductor) affect power dissipation:

- The results clearly show that as frequency increases, the power dissipated per unit length also increases as the Y/D ratio increases. This, is consistent for both Y/D although having different amplitudes 0.70- and 1-mm peak to peak.
- Greater (Y/D ratio) means greater energy dissipation, resulting in more intense internal friction.
- The study reveals that vibration frequency and amplitude play a key role in the conductor's ability to self-dampen.

Indeed, the results underline the importance of understanding the interaction between vibration frequency, amplitude and energy dissipation in order to design more efficient and durable conductive systems.

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