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INVESTIGATIONS ON OVERHEAD POWER LINE CABLES HEALTH MONITORING

MASTER'S THESIS

by

Sergi GONZÁLEZ PRUNERA

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Supervisor: Dr. Jean-Louis LILIEN

Université de Liège
Faculty of Applied Sciences
Sergi González Prunera

Master's Thesis

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ABSTRACT

This work deals with the health monitoring of overhead power lines conductor's technologies. In particular, the scope of the present Master's Thesis is to develop a method to catch the damping from a given register of data. The data represents the vibration of overhead power line conductor. The method tested is the Prony's Method.

The thesis is structured in two main blocks. The first is composed by chapters from 1 to 4. The information included is a state of the art of the current technologies applied in ambient vibration monitoring of bridges, suggesting how to apply them in cable monitoring (chapter 1), an introduction to the Aeolian vibration phenomenon (chapter 2), a brief introduction to the basic theoretical bases of the vibration movement (chapter 3) and, finally, a chapter dedicated exclusively to the self-damping in conductors, explaining what is it, and how to measure it (in laboratories) and to evaluate it (chapter 4).

The second block is related to the investigations done. It is composed by chapters from 5 to 11. It includes the description of the data used (chapter 5), a complete explanation of the preprocessing and processing of the data (chapters 6, 7 and 8), the presentation of the results obtained (chapter 9), some conclusions (chapter 10) and recommendations for further work (chapter 11).

The main conclusion is that the Prony's Method is not suitable to determine the self-damping coefficient of the vibration data.

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FOREWORD

This thesis was carried out at the Faculty of Sciences of the Université de Liège in fulfilment of the requirements for acquiring a degree in Industrial Engineering in Electricity.

The aim of this thesis is to develop a method to obtain the self-damping coefficient of overhead power line conductors by means of analysing raw vibration data recorded with accelerometers. For this reason, data must be converted from acceleration to displacement, and must be filtered before applying the method which enables to obtain the coefficient. The method tested has been the Prony's Method.

I would like to express my very great appreciation to Dr. Jean Louis Lilien for his valuable and constructive suggestions during the planning and development of this work. He has always been available when I needed to meet him.

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Sergi González Prunera

LIST OF SYMBOLS

| Symbol | Description | S.I. Units |
|-------------|---|---|
| V_S | Onset aeolian vibration wind velocity | [m/s] |
| f_n | Modal frequency | [Hz] |
| d | Diameter of the conductor | [m] |
| S | Strouhal number | [-] |
| m | Mass matrix | [kg] |
| EI | Bending stiffness | [Nm ²] |
| r | Damping matrix | [Ns/m] |
| c | Stiffness matrix | [N/m] |
| ω | Cyclic undamped frequency | [rad/s] |
| D | Damping according to Lehr | [-] |
| a | Parameter for the damping matrix | [1/s] |
| b | Parameter for the damping matrix | [s] |
| F | Force developed between the cable and the shaker | [N] |
| μ_F | Displacement of the forcing point | [m] |
| \emptyset | Phase between F and μ_F | [rad] |
| P | Power dissipated per unit length | [W/m] |
| ζ | Self-damping coefficient | [-] |
| L | Length of the span | [m] |
| ω | Circular natural frequency | [rad/s] |
| m_L | Mass per unit length | [kg/m] |
| S_i | Ratio between the amplitudes of vibration of a node and an antinode | [-] |
| V | Wind velocity | [m/s] |
| n_v | Number of nodes | [-] |
| λ | Wave length | [m] |
| T | Tension in the cable | [N] |
| δ | Logarithmic decrement | [-] |
| l | Parameter of the power law | [-] |
| m | Parameter of the power law | [-] |
| n | Parameter of the power law | [-] |
| k | Parameter of the power law | [-] |
| C_* | Self-damping equation parameter | [s ⁴ /kg ² m ²] |
| N | Tension in the conductor | [N] |
| δ | Self-damping equation parameter | [-] |
| γ | Self-damping equation parameter | [-] |
| ξ | Self-damping equation parameter | [-] |
| β | Self-damping equation parameter | [J] |
| y_{max} | Antinode zero to peak amplitude | [m] |
| σ_i | Damping component of the PM definition | [1/s] |
| N | Model order for the PM | [-] |

LIST OF ABBREVIATIONS

| Abbreviation | Description |
|--------------|---|
| AAAC | All Aluminum Alloy Conductor |
| ACSR | Aluminum Conductor Steel-Reinforced |
| AVM | Ambient Vibration Monitoring |
| DFT | Discrete Fourier Transformation |
| DM | Decay Method |
| EBP | Energy Balance Principle |
| FEM | Finite Element Method |
| FFT | Fast Fourier Transformation |
| IDFT | Inverse Discrete Fourier Transformation |
| ISWR | Inverse Standing Wave Ratio |
| MDOF | Multiples Degrees of Freedom |
| PM | Prony's Method |
| PwM | Power Method |
| SDOF | Single Degree of Freedom |

PREFACE

We live in a world that is in a continuous development. Everyday new devices are released to the market and new technologies are developed. A major problem that concerns all of us is that these developments are attached to an increase of the global energy consumption and more specifically of the electrical energy consumption. For this reason there is a need to achieve a greater generation of electricity and also to increase the efficiency of all the electrical devices to be able to satisfy all the requirements.

The electrical system has been historically constituted by huge electricity power plants located far away from the consumption nucleus. The energy was transported from the power plants to the consumption nucleus in high voltage power lines with alternative current.

The growth in demand of energy leads to an increase of its generation, by building new power plants and also with the increase of the renewable energies. This will lead to a need of construction of new power lines to distribute the extra power generated. Nevertheless, the present infrastructures were built several years ago when the technology was not as developed as it is nowadays. These power lines were constructed with a big margin of security in order to avoid overloading problems that could not be predicted.

One line of the current work for utilities and investigation centers is to develop technologies that enable a more efficient use of the already available power lines. In this way there already exist some real-time monitoring technologies that are able to predict for example when overloads of power will occur or to detect when a problem can potentially occur.

The environment of the present Master's Thesis is the health monitoring of overhead power lines. Furthermore, to be more specific, the scope of the Thesis is to develop a method that permits to catch the damping of the data obtained in power lines conductors' vibration monitoring.

1. AMBIENT VIBRATION MONITORING (AVM)

In engineering it is important to be able to have a global vision. This means that one should not focus in just one discipline. Theory, procedures and techniques developed for a specific area of engineering may be also applied in other areas if they are suitable adapted. This chapter presents some techniques used in health monitoring of bridges and suggest how to apply them to health monitoring of overhead power lines cables.

Even though there exist great varieties of software that can be used to model structures, allowing the possibility to get an estimation of the behavior of a structure under different loads is not enough. The softwares use models and consequently they do not represent the entire reality. It is therefore necessary to get real information of the real state of the structure. The data obtained is then suitable processed in order to get useful information applying different mathematical models.

The state of the art of ambient vibration monitoring (AVM) in bridges will be considered in order to be able to apply similar techniques afterwards in overhead power lines cables. The scope of AVM is to use the dynamic behavior of a structure in order to assess its condition and capacity. This is achieved by extracting the information of the data collected by highly sensitive acceleration sensors strategically situated on different points of the structures. The main reference to write this section is the book *Ambient Vibration Monitoring* [1].

Before going on, one consideration must be done. In this chapter the majority of the techniques explained make reference to technology applied to bridges. For this reason, when the word *structure* appears is principally referred to bridges. After every technique explanation there is a suggestion of how to apply the technique for power lines if it is possible or necessary.

1.1. Objectives of applications

AVM of bridges and power lines is used for health monitoring tasks. Next there is a list of the tasks that comprise AVM procedures.

- System identification.
- Stress test.
- Assessment of stresses.
- Load observation (determination of external influences).
- Monitoring of the condition of structures.

These techniques are further explained in the following paragraphs, each one individually.

1.1.1. System identification

The system identification consists in carrying out dynamic measurements of ambient structure vibrations in order to obtain the dynamic characteristic of the structure. Highly sensitive acceleration sensors are used to record the vibration behavior of the structure without artificial excitations. A good system identification in bridges can be done by determining the following:

- **Eigenfrequencies and mode shapes.** These parameters are essential to determine the behavior of the structure. The mode shapes are the vibration form in which the structure oscillates in a specific eigenfrequency (every eigenfrequency has its own mode shape). Both of them can be obtained mathematically from the data measured. Furthermore, the mode shapes can also be obtained experimentally measuring the deformation of the bridge point by point. A further explanation is done in subchapter 3.1.
- **Damping.** The damping can be defined as the mitigation of the vibration of a structure due to external excitations (e.g. the cars crossing a bridge or the wind transmitting mechanical energy to a cable) until a static equilibrium is reached. Damping is a very important value for system identification because it is an indicator of the current degree of exploitation of the load-bearing capacity of a structure. In addition, damping properties are dependent on the vibration frequencies. In 3.2 there is a further explanation of the damping concept.
- **Deformations and displacements.** It is possible to obtain information of deformations and displacements in the three dimensions, which is to say that it is possible to obtain vertical and horizontal information. That is useful to determine the flexural stiffness of a structure.
- **Vibration intensity.** This information is useful to determine the stress of a structure. The higher the intensity of the vibration the higher the possibility of having damage. Furthermore, assessment of vibration intensities can give information about of fatigue of the structures and also an indication of the lifetime of the structure. The vibration intensity is usually presented in an intensity chart classified in groups of susceptibility to damage.
- **Trend cards.** Trend cards are a visual representation of the vibration frequencies in the time domain. They are useful to identify the frequency peaks.

1.1.2. Stress test

A stress test must be done in order to assess the stress condition of a structure and its individual load-bearing elements. This test enables to know the current safety level of the structure and its elements and thus it is possible to decide if it is necessary to introduce immediate measures or what kind of maintenance task is

required to be done. In bridges it is important to determine the stress statically and dynamically. Thus it is possible to determine the traffic loads.

For those elements that have a direct relation between their eigenfrequencies and their stress level (e.g. cable-bridges) it is possible to determine the stress from the vibration measures. For the assessment of cables it is also important to determine the forces that it bears. There is a quasi linear relation between the eigenfrequencies of a cable and their inherent force, so it is possible to do an approximation of the force of the cables from its vibration measurement.

It must not be confused when the word cable is used talking of bridges or of power lines. The cables of bridges can be more rigid and they work at a considerably higher stress than the cables of the power lines. Since the latter are not working at high stresses it is not necessary to do any kind of stress tests to them.

1.1.3. Assessment of stresses

Assessment of stresses is done for the whole structure and also for the individual structural members. When an assessment of a structure is done it should provide information about the actual condition of the structure and should also consider the future development of the structural condition.

To determine the safety of a structure an analysis of its dynamic characteristic must be done. That is to say that the frequencies and their respective mode shapes must be found and then calculate the damping values that describe the system behavior. This analysis is focused mainly in the lower frequencies. The same is done for individual structural members. By the way, it is possible to make predictions by applying probabilistic approaches based on data recorded on previous analyses. These predictions are trustable on the triple period of measurements (i.e. in the case of measurements over three years, an extrapolation of nine years). For that reason measures must be carried out periodically considering that the first time that the structure is measured must be as soon as possible.

In the case of the conductors of a power line it is also important to make a dynamic analysis in order to obtain the eigenfrequencies, eigenmodes and the damping of the cable vibration, but as it has been discussed in the previous point (*stress test*) the assessment of the stress is not critical. Nevertheless it is useful to know it when applying some methods to calculate the damping because it is a variable that makes influence in the models.

1.1.4. Load observation (determination of external influences)

The load observation consists in the determination of external influences. In bridges the most important influences are the traffic loads. These influences are registered by the dynamic response of the structure.

It is difficult to design a load model correctly before constructing a structure. The models improve clearly when there exist measured data. This is because when there is data available it is possible to compare the results obtained with the model with the results obtained from measured data.

In cables the dynamic behavior is defined by its free vibration length, its mass and the inherent force according to the cable theory if the cable is without any bending stiffness.

In power lines there are no traffic loads but it is the wind who must be considered. There can also exist other external loads such ice or snow. It is important to do a good monitoring of these facts so that the working of the line is not stopped. For that there already exist some techniques to prevent problems.

1.1.5. Monitoring of the condition of structures

There are different ways to monitor the structural properties of a structure. AVM considers that the observation should cover long periods. However, it is possible to monitor the structures periodically or permanently.

For periodic monitoring it is advisable to do a first basic measurement in order to identify the system. Then measurements should be executed at variable periods depending on the condition of the structure. The measures recorded can be then compared to the basic measurement in order to make conclusions about the state of the structure.

If the structure can be easily in trouble, i.e. if a minor change in a structural member can lead to serious consequences; it is possible to do permanent monitoring. Afterwards the data recorded can be sent in real time by gsm signal to a computer localized in another place in order to be able to process the information properly and make the corresponding decisions.

Power lines must be permanently monitored. The power flows must be controlled by the utilities in a real-time mode. Consequently, there must be sensors in the lines monitoring it. It is also important to do a monitoring of the mechanical health of the line. This monitoring should also be done permanently in order to avoid phenomena like galloping or icing.

1.2. Practical Measuring Methods

When monitoring tasks are going to be performed some points must be considered. The first thing is that the measurements will be realized with very sensitive acceleration sensors. It also is important to consider how many sensors will be needed for a correct monitoring and also if it will be just for an established period of time or if it will be a real time monitoring, which entails to fix the sensor in the structure. This must not influence in the stiffness of the structure where they are fixed.

The location of the sensors should be also planned. In bridges it is advisable to previously know the behavior of the structure in order to arrange the sensors in the right points of the structure. That is because there may be parts of the structure which are more critical and thus require a higher density of sensors to obtain the maximum information.

Furthermore, the mass of the sensors must not be too large in order to not influence the system behavior. They must be robust enough in order to support without problems their operation conditions like temperature, humidity or mechanical stresses.

The results obtained with the sensors should be compared with an external observation in order to verify them. For example if a displacement of a point of a bridge is recorded, it should be compared to the displacement recorded by a topographer.

For overhead powerlines the general idea in order to do practical measures is very similar to that of bridges. It must be considered how many sensors are needed and where to put them. It is also advisable that the mass of these sensors is not high enough to make an influence to the results. Finally it is also useful to calibrate the sensors to compare the results measured with those of a topographer.

In overhead power line cables monitoring this is simpler if the AMPACIMON® sensors are used. They are directly clumped in the cable and their location is not important for their calculation.

2. AEOLIAN VIBRATION

In health monitoring of overhead power line cables it is very important to obtain data about vibration. This data will enable us to find and calculate important parameters for a correct assessment of the power line. The vibration is principally due to the wind and is closely related to the damping ability of the conductor. A brief introduction to aeolian vibration and its characteristics is found in this section. There is also one subchapter introducing the conductors and another introducing the bending stiffness concept. The main reference to write this section is the second chapter of the *Orange Book* [2]. To know more about the subject, please check the literature.

Aeolian vibrations can occur almost in any time in low to moderate winds. They represent the major cause of fatigue failure of conductor strands or of items associated with the support, use, and protection of the conductor.

Furthermore, aeolian vibration is the vibration of a cable that is induced by the wind. Each eigenfrequency has his trigger wind speed where its vibration starts. Moreover, for a suitable understanding of this phenomenon it is necessary to know which characteristics interact with the aeolian vibration. These elements are the wind, the vortex-shedding mechanism, the cables and their mechanical properties and also the damping devices.

2.1. Vortex-shedding mechanism

Ignoring other kinds of energy inputs and also ignoring losses, the energy dissipated by the conductors by means of vibration is the same energy that is caught from the wind by the aeolian vibration mechanism. This is known as the Energy Balance Principle (EBP) and is used in most analytical models because it gives a good approximation.

But how is it possible that with a horizontal wind blowing laterally to one cable at a certain speed it starts vibrating vertically? It can be explained with theory related to fluid dynamics. Concretely, it is due to the vortex-shedding mechanism.

The vortex-shedding is generated when a fluid interacts with a cylindrical body, in this case the conductor. It consists in a flow composed with vortices that is generated behind the body where the fluid impacts. These vortices appear “one up, one down” and they do it repetitively following a specific period depending on the wind speed. Thus, there also appears a periodic variation of the pressure on the surface of the body. The body tends to move to the place where the pressure is lower and since it is changing all the time the body starts to vibrate. Nevertheless, it does not really start to move until the frequencies of the vortices shed approaches a modal frequency of the conductor.

For the cable starts to vibrate the wind must blow at a certain velocity that is known as the onset velocity (V_S). It is possible to find the onset velocity for each modal frequency (f_n). This can be calculated by equation (1), that is the Strouhal

Number (S) definition. Strouhal Number can take the values from 0.18 to 0.22, but in the range of Reynolds' number at which Aeolian vibration occurs, this value is $S = 0.18$. The variable d represents the diameter of the conductor.

$$V_S = \frac{f_n \cdot d}{S} \quad (1)$$

Since the conductor starts to vibrate a lock-in effect occurs and the vortex-shedding frequency is controlled by the conductor vibration, even though the velocity of the wind changes. This happens for values of the wind speed comprised between $0.9 \cdot V_S$ and $1.3 \cdot V_S$.

When the vortex shedding phenomenon occurs in a conductor the typical values for the frequency are comprised between 3 Hz and 200 Hz. Moreover, the vibration amplitudes can be as much as the diameter of the conductor for the lower frequency values.

2.2. Conductors

The conductors or cables are considered the most important part of the power lines since they are the only elements that are able to transport the electrical power and their cost can be up to the 40 % of the total cost of the structure. They are submitted to electrical, mechanical and environmental loads during their life and so it is important to consider which materials are used to construct it and also their layout and design.

The most typical materials nowadays used to construct the conductors are aluminum and aluminum alloys. Their construction form is usually a composition of layers of round wires stranded around a nucleus that can be of the same material or another (e.g. steel) and then every layer around each other alternating the direction of the stranding in order to keep the integrity on this construction. See figure 2.2.1. Normally the wires are round-shaped, but there also exist other shapes that are used to construct conductors, like trapezoidal or z-shaped conductors. These are constructed with a nucleus of round wires and the most external layers are composed with those differently shaped wires.

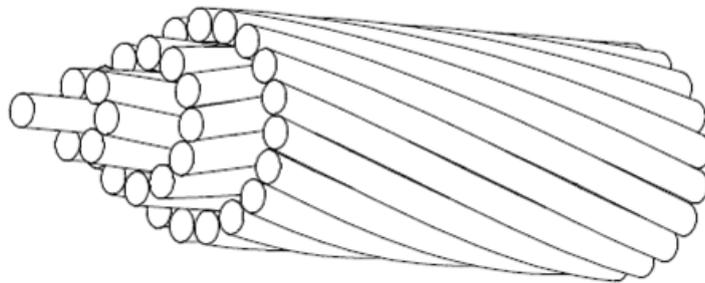


Figure 2.2.1. Image of a stranded conductor. (Source: "Orange Book")

The electrical parameters that influence the design of the conductor are the current density, and the power loss and voltage gradient due to the electrical resistance. These can be solved by adding area and adjusting the outside diameter of the conductor and also it is possible to use multiconductor bundles. But the most of the requirements considered for a good conductor design come from the mechanical constraints.

2.3. Bending stiffness

The bending stiffness EI of a single wire is defined by the product of the moment of inertia (relative to a given axis) of its section and the Young's modulus of its material. As it has been said in section 2.2, nowadays the majority of the conductors are made up with stranded wires.

When calculating the bending stiffness of a conductor two theoretical values can be obtained, the maximum and the minimum bending stiffness. On the one hand, for the maximum value it is assumed that all the wires act together as a solid. On the other hand, the minimum value is calculated assuming that all the wires act independently. The following lines contain the general process to calculate the maximum bending stiffness.

The bending stiffness of a conductor can be expressed as the sum of the bending stiffness $E_i I_i$ of all the n different wires related to the same axis, the neutral axis. See equation (2).

$$EI = \sum_{i=1}^n E_i I_i \quad (2)$$

The moment of inertia I_i for a single cable is defined by equation (3).

$$I_i = I_{0i} + A_i d_i^2 \quad (3)$$

The variable A_i represents the area of the wire i , I_{0i} is the moment of inertia of the wire related to his own neutral axis and d_i is the distance between the wire and the conductor neutral axes. The distance d_i is calculated with equation (4).

$$d_i = r_n \sin(\alpha) \quad (4)$$

The parameters which appear in the previous equation are represented in figure 2.3.1.

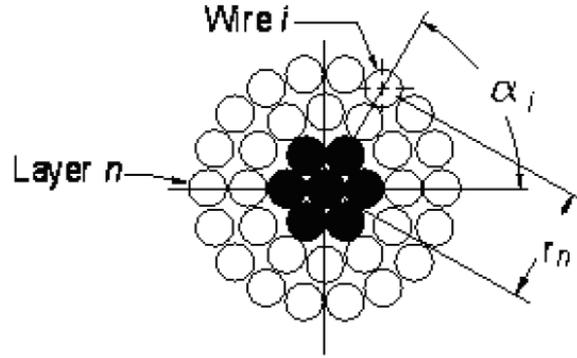


Figure 2.3.1. Stranded conductor section with parameters to calculate the distance between the wire's and the conductor's neutral axes. (Source: Orange Book)

The final expression for the maximum bending stiffness is the one in equation (5).

$$EI = \sum_{i=1}^n E_i (I_{0i} + A_i r_n^2 \sin^2(\alpha_i)) \quad (5)$$

Considering that for the minimum bending stiffness the assumption made is that all the wires act independently, there is no influence of the wires to the neutral axis of the conductor. Thus the expression for the minimum bending stiffness EI_{min} is in equation (6).

$$EI_{min} = \sum_{i=1}^n E_i I_{0i} \quad (6)$$

The procedure that has been explained above works perfectly for conductors made entirely with round wires. However, for z-shaped wires the estimation of the bending stiffness is quite more complicated. On the one hand, every single z-shaped wire bends around its own neutral axis. On the other hand, the shape of these wires does not allow the calculation of their moment of inertia by simple calculation. Moreover, to improve the performance of the conductor under the effects of aeolian vibrations and to improve the slippage between the layers of wires, there is grease within the wires. The impact that this fact has on the calculation of the bending stiffness is difficult to quantify, even though there exist some software programs that can give an approximate value [3].

3. BASIC THEORETICAL BASES

To be able to perform a correct health monitoring of the overhead power line cables a dynamic analysis of them must be carried on. This is because the variable monitored is the vibration of the conductor, which is a dynamic parameter. In this section there is an explanation of the most important dynamic parameters that define the vibration and can be afterwards used to assess the health of the line. These are the eigenfrequencies, their corresponding mode shapes, and also the damping. The relationship between damping, stiffness and mass of the conductor are explained with the viscously damped free oscillatory vibration problem. For this chapter the main reference used is [1].

3.1. Eigenfrequencies and mode shapes

The determination the eigenfrequencies and the mode shapes of a structure can be carried out using different mathematical methods. That is called modal analysis. The different existing approaches work with the hypothesis that the structure has a linear behavior. The most extended one nowadays is the finite element method (FEM), but it is also possible to perform energetic approaches with the Rayleigh method applied to single (SDOF) or multiple degrees of freedom (MDOF) systems.

Furthermore, there is another possibility to make an estimation of the eigenfrequencies of a structure from the recorded acceleration measured. Those accelerations are recorded on the time domain and can be transmitted to the frequency domain using the Discrete Fourier Transformation (DFT), for example, and afterwards find the eigenfrequencies of the structure because there will appear energy peaks next to these frequencies.

The mode shapes can be defined as the vibration forms corresponding to each eigenfrequency. They are the second essential parameter used to describe the dynamic behavior of a structure. The mode shapes are obtained from the same acceleration data where the eigenfrequencies are calculated. However, the procedure is different. Here the acceleration data is integrated twice in order to obtain the vibration distances of the point where the sensor is placed. Afterwards the data obtained are transformed to the frequency domain. Finally the mode shape is draw considering the resulting displacement calculated for every eigenfrequency in the different points where the sensors had been placed.

3.2. Damping

Damping is a dynamic parameter that represents the mitigation of a vibrational movement. This is the third value that can be obtained from the acceleration data and can therefore be used to assess the state of structures or conductors. In the following paragraphs there is a clear explanation of the damping concept, including a

theoretical development and the different methods that can be used in order to obtain a damping coefficient.

Damping can also be understood as a measure of the capacity of a system to dissipate energy. For example in an oscillating pendulum that only receives an impulse to start its movement and has no external forces applied it can be imagined the following cases. If there exists no damping the system will keep on moving the same way all the time because there will not be any energy losses. If there exist damping the pendulum will lose its energy and it will do a shorter path each time that it changes its direction. Finally the pendulum will stop in its equilibrium position. The higher the damping would be the faster the pendulum would stop.

3.3. Viscously damped free oscillatory vibration problem

In order to understand the theory the first step will consist in the explanation of the viscously damped free oscillatory vibration problem with a single degree of freedom (SDOF). Firstly it will be considered the classic spring vibration problem see figure 3.3.1. That problem is modeled with the following ordinary differential equation (ODE) (7),

$$m \cdot \ddot{x} + r \cdot \dot{x} + c \cdot x = F(t) \quad (7)$$

where m , r and c represent the mass of the body, the damping and the constant of the spring, respectively. The variable F represents the external forces and is variable with the time t . The other variables represent the velocity \dot{x} (equation (8)) and the acceleration \ddot{x} (equation (9)) are defined as follows,

$$\dot{x} = \frac{dx}{dt} \quad (8)$$

and

$$\ddot{x} = \frac{d^2x}{dt^2} \quad (9)$$

The solution of the ODE $x(t)$ is given by the sum of the solution of the corresponding homogeneous equation $x_h(t)$ and the particular solution $x_p(t)$. See equation (10).

$$x(t) = x_h(t) + x_p(t) \quad (10)$$

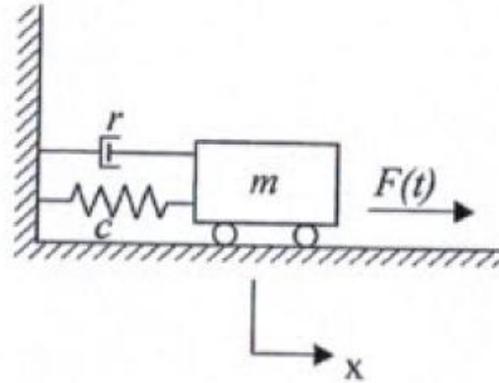


Figure 3.3.1. SDOF spring vibration problem. (Source: AVM book)

There exist multiple numerical methods to solve the differential equations. This thesis will not focus deeply in the mathematical procedures and theories but it will pay more attention in which programs or tools can be used to solve the problems.

From the equation (7) can be figured out that the damping r in this model is linearly dependent of the speed of the movement of the body.

Some parameters like the natural cyclic undamped frequency ω or the damping according to Lehr D can be figured out from the data available. These are defined below in equations (11) and (12).

$$\omega = \sqrt{\frac{c}{m}} \quad (11)$$

$$D = \frac{r}{2\sqrt{m \cdot c}} \quad (12)$$

From those parameters it is possible to obtain the transformed equation of motion by working on equation (7). The result is the following.

$$\ddot{x} + 2 \cdot D \cdot \omega \cdot \dot{x} + \omega^2 \cdot x = \frac{F(t)}{m} \quad (13)$$

After explaining the SDOF case of the problem it is necessary to generalize the case by explaining the same problem but with multiple degrees of freedom (MDOF).

To figure out how a MDOF system can be seen figure 3.3.2. In this case, the parameters m , r and c used in the SDOF system become the mass, damping and stiffness matrices respectively. The variables x , \dot{x} and \ddot{x} become vectors. Regarding the figure 3.3.2. the matrices would be like the following.

$$[m] = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \quad (14)$$

$$[c] = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 \\ -c_2 & c_2 + c_3 & -c_3 \\ 0 & -c_3 & c_3 \end{bmatrix} \quad (15)$$

$$[r] = a \cdot [m] + b \cdot [c] \quad (16)$$

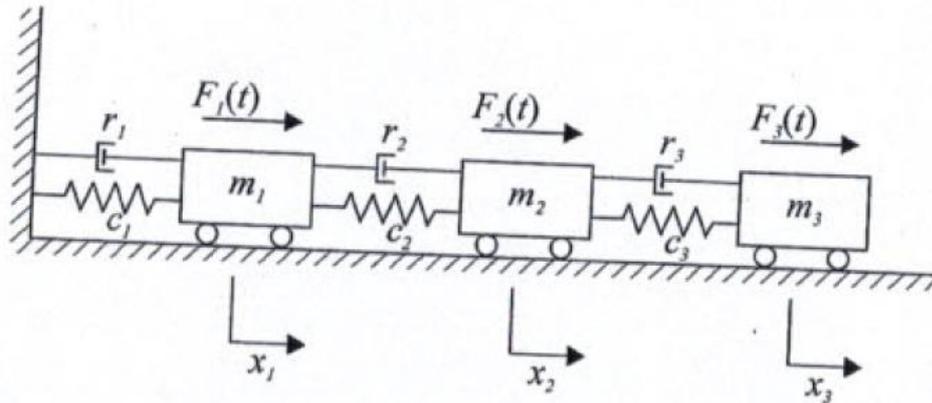


Figure 3.3.2. MDOF spring vibration problem. (Source: AVM Book)

The parameters a and b from the damping matrix r are constants. That means that the damping is physically proportional to the mass and the stiffness. The equation of motion is found below (equation (17)).

$$[m] \cdot [\ddot{x}] + [r] \cdot [\dot{x}] + [c] \cdot [x] = [F(t)] \quad (17)$$

To reach a solution the first step to follow is to decouple the system of differential equations and then solve each resulting equation separately. This is done by determining the eigenfrequencies and the mode shapes by solving the eigenvalue problems. See equation (18).

$$([c] - \omega_i \cdot 2 \cdot [m]) \cdot [a_i] = 0 \quad (18)$$

The total solution is obtained by the superposition of the individual solutions.

4. DAMPING IN CONDUCTORS

This chapter is going to focus more specifically in the damping that takes place in conductors. First there is an explanation of the conductor self-damping. Later some techniques applied in laboratory tests to measure the self-damping are explained. Finally a new formula to evaluate the self-damping power dissipation is introduced. The main source to develop this section has been the second chapter of the “*Orange Book*” [2].

4.1. Conductor self-damping

The conductor self-damping is the property that have conductors to dissipate the mechanical energy absorbed from the wind while vibrating by their own. This definition is not considering the help that can give some absorbing energy devices like vibration dampers that are commonly used in power lines. Furthermore the knowledge of the self-damping of a conductor can be useful to determine the range of frequencies where the dampers may be needed.

The dissipation of energy is produced for structural causes but the general idea is that the mechanical energy from the wind is transformed into heat. This is mainly because of the contact that exists between the multiple strands of a cable and the friction forces generated between them when the cable vibrates. Furthermore, there also exists damping due to the material of the cable but this damping is less important than the damping due to the relative movement between the strands.

Another important characteristic of the conductor self-damping is that it is not linear. It appears as a curve if the dissipated energy is plotted against the resulting conductor strain or amplitude. By the way, if these results are plotted on a log-log chart the results appear as a fairly straight line.

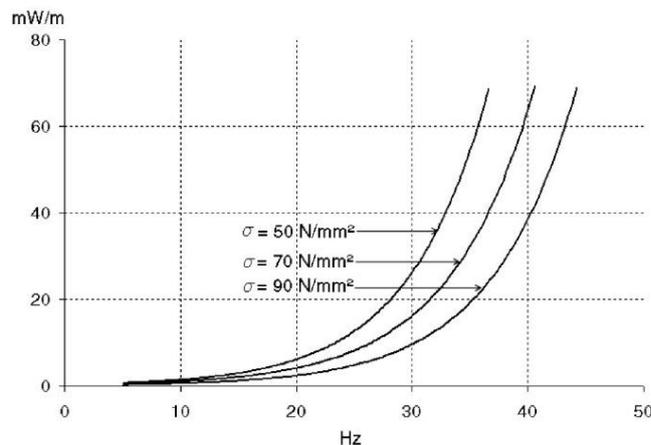


Figure 4.1.1. Self-damping of ACSR 564/72 over the frequency for various conductor tensions at a free span angle. (Source: “*Orange Book*”)

The mechanical tension of a cable is another factor which influences its damping capacity. As it can be seen in figure 4.1.1. for a given frequency the self-damping is decreased as the tension is increased. Another fact observable is that the higher the frequency of vibration the higher the difference in damping capacity for different tensions.

4.2. Measurement of the self-damping in conductors

The following paragraphs explain some of the methods used in laboratories to measure the self-damping of conductors. The tests are normally composed of two blocks where a conductor span (between 30 and 90 m) is strung with a given tension, a vibration generator and the corresponding measuring devices. Different tensions are tested because the self-damping of the conductor is influenced by that. For each different tension that is tested the conductor is excited with different vibration frequencies (the frequencies of resonance).

The power method (PwM), the inverse standing wave ratio method (ISWR) and the decay method (DM) are introduced below.

4.2.1. Power Method (PwM)

This method is based in the fact that when the conductor reaches a stationary condition, the energy dissipated by the conductor is the same that the energy introduced by the shaker. This energy is calculated using the equation (19), where F is the force developed between the cable and the shaker, μ_F is the displacement of the forcing point and \emptyset is the phase between F and μ_F .

$$E_{introduced} = E_{dissipated} = \pi \cdot F \cdot \mu_F \cdot \sin(\emptyset) \quad (19)$$

Equation (20) is used to calculate the power dissipated (P_{diss}) by the conductor per unit length, where f is the natural frequency at which the cable is excited and L is the length of the laboratory span.

$$P_{diss} = E_{diss} \cdot \frac{f}{L} \quad (20)$$

The self-damping is represented by a non-dimensional damping coefficient, ζ . It is calculated with the following equation (21).

$$\zeta = \frac{1}{4\pi} \cdot \frac{E_{dissipated}}{E_{k,max}} \quad (21)$$

Where $E_{k,max}$ is the maximum kinetic energy of the cable. It is calculated with the following equation (22), where ω is the circular natural frequency ($\omega = 2\pi f$), m_L is the mass of the conductor per unit length and y is the antinode vibration amplitude.

$$E_{k,max} = \frac{1}{4} \cdot m_L \cdot L \cdot \omega^2 \cdot y^2 \quad (22)$$

For a correct determination of the self-damping of a cable it must be considered that the loops at the ends of the span and at the both sides of the shake behave differently from the rest of the free span. In these portions of the conductor there occurs a higher dissipation of energy than in the rest of the span, and therefore this fact must be considered by separating the endpoint damping from the free-span self-damping. The end-loop problem can be avoided by mounting the span termination on 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.

4.2.2. Inverse Standing Wave Ratio Method (ISWR)

This method consists in measuring the displacement of the nodes and the antinodes of the span in order to calculate the mechanical power flowing in one section of a cable, P_i . The advantage of the ISWR method against the PM, is that the dissipation obtained from a calculus only relates to the considered portion of the cable measured. The main problems are related to the precision in measuring the amplitude of vibration of the nodes, which can be of only a few micrometers. An error in the measuring of the antinode vibration can change the self-damping estimation.

In the case of ISWR the shaker is attached near of one of the span terminations. The shaker creates waves that arrive to the end of the span and then are reflected. In the case that no losses were present the incident and the reflected waves would be equal. Furthermore, the movement in the nodes would be inexistent and the vibration amplitude in the antinodes would be equal to the sum of the reflected and the incident waves. In reality losses are present and therefore there exists motion in the nodes which amplitude is the difference between the incident and the reflected waves.

The following equation (23) is used to calculate the mechanical power P_i flowing in one section of the cable, where T is the tension of the cable.

$$P_i = \frac{V^2}{2} \cdot S_i \cdot \sqrt{T \cdot m} \quad (23)$$

Where,

$$V = \omega \cdot y \quad (24)$$

And,

$$S_i = \frac{a_i}{y} \quad (25)$$

The parameter S_i is the ratio between the amplitude of vibration in a node (a_i) and the amplitude of vibration in an antinode (y). This ratio is indicative of the dissipation within the system.

It is possible to calculate the power dissipated between the nodes k and j by using equation (26).

$$P = P_k - P_j \quad (26)$$

If the parameter of interest is the power dissipated per length unit equation (27) is suitable, where n_v is the number of nodes between k and j and λ is the wave length.

$$P_{diss} = \frac{P_k - P_j}{n_v \cdot \frac{\lambda}{2}} \quad (27)$$

The following expression calculates the kinetic energy of the portion of a cable between the two nodes.

$$E_{k,max} = \frac{1}{2} \cdot y^2 \cdot \omega^2 \cdot \frac{m_L}{4} \cdot \frac{1}{f} \cdot \sqrt{\frac{T}{m_L}} \cdot n_v \quad (28)$$

Finally, the value of the non-dimensional self-damping coefficient ζ is given by equation (29).

$$\zeta = \frac{S_k - S_j}{\pi \cdot n_v} \quad (29)$$

4.2.3. Decay Method

The decay method can give a first approximation of the value of the self-damping at all amplitudes in one trial. It requires one vibration transducer measuring the decay after the exciter.

As in the other methods explained, the exciter is forced to vibrate at one of the span's natural frequency. After that, it is stopped and the decay is measured. If the system is lightly-damped ($\zeta \ll 1$) then the decay trace looks like figure 4.2.3.1.

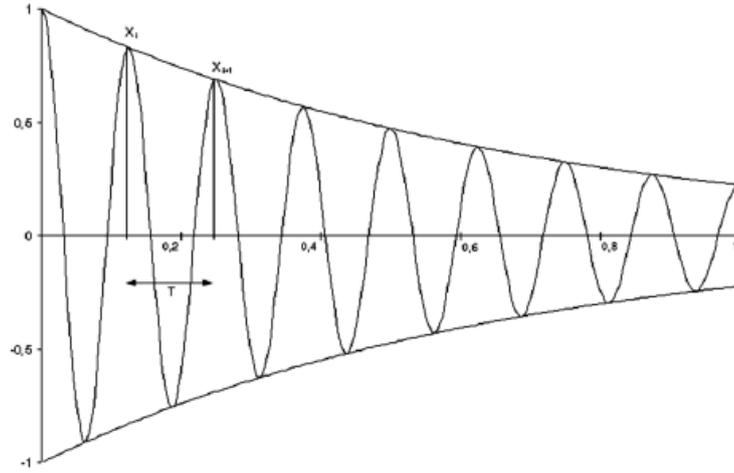


Figure 4.2.3.1. Decay trace. Source: "Orange Book".

Regarding the figure 4.2.3.1, the logarithmic decrement (δ) is calculated considering two successive peaks using the expression below.

$$\delta = \ln\left(\frac{X_i}{X_{i+1}}\right) = \ln\left(\frac{e^{-\zeta\omega_0 t} \cdot |X| \cdot \cos(\omega t + \phi)}{e^{-\zeta\omega_0(t+T)} \cdot |X| \cdot \cos(\omega(t+T) + \phi)}\right) \quad (30)$$

It is possible to simplify the expression, so the final result is like the following.

$$\delta = \ln(e^{\zeta\omega_0 T}) = \zeta\omega_0 T \quad (31)$$

For lightly damped cables the tension T can be considered as a function of ω_0 resulting in the following expressions for the tension and the self-damping coefficient.

$$T = \frac{2\pi}{\omega_0} \quad (32)$$

$$\zeta = \frac{\delta}{2\pi} \quad (33)$$

In some frequencies it is possible that some of the energy introduced by the shaker to create a vertical motion is transferred to horizontal motion. This fact would lead to a mistaken measure, so one solution would be to use also a horizontal transducer in order to record the horizontal losses. However, this phenomenon usually occurs at certain frequencies that are not prevalent enough to influence the entire program and these frequencies can also be easily avoided.

4.2.4. Some considerations

It have only been explained some methods to find the self-damping of a conductor but all of them are carried in a laboratory. In the laboratory it is easy to know the vibration frequency of the cable since it is given by the shaker that is programmable. The issue of this Master's Thesis is to develop a tool or a method that given vibration data of a real power line is able to calculate the damping for every instant in time, since the vibration may be changing fast depending in the conditions of the wind. In the following chapters the process applied to find the damping in real vibration data will be explained as so as how it has been evaluated.

4.3. Evaluation of the conductor self-damping

Once the data vibration data has been recorded and properly analyzed in order to obtain the self-damping coefficients, the results must be evaluated. To do it, one of the models to predict the self-damping dissipation power must be used. The power dissipated due to self-damping is directly proportional to the amplitude and frequency of vibration. Moreover, it is inversely proportional to the tension in the conductor. This relationship is clearly expressed via the "power law", as it can be seen in equation (34).

$$P_{diss} = k \frac{y_{max}^l f^m}{T^n} \quad (34)$$

P_{diss} is the self-damping power dissipated per unit length, y_{max} is the antinode zero to peak amplitude, f is the frequency of vibration and T is the tension in the conductor. The parameters k, l, m and n are different for each single conductor. However, they can be determined in short laboratory spans and then they can be extrapolated to much longer spans.

The "power law" is widely used because it enables to split the power dissipated by the conductor itself. The current data used for this present work has already been analyzed with this method; the results can be consulted in [4].

A new model for the self-damping power dissipated has been proposed in [4]. To see how it has been achieved please look to the reference. In this model P_{diss} is a function of the antinode amplitude of vibration, the frequency, the conductor tension, the bending stiffness, the mass per unit length and a parameter called β (which is measured in Joules). See equation (35).

$$P_{diss} \approx \frac{1024}{9} \gamma^2 (C_* N)^{\delta+1/2} \xi^2 \pi^5 \beta y_{max}^3 m^3 f^7 \frac{EI}{N^4} \quad (35)$$

In this equation γ, δ and ξ are non-dimensional parameters, m represents the mass per unit length [kg/m], N is the tension of the conductor [N], EI is the bending

stiffness [Nm^2], and C_* is a parameter with amplitude 1 that makes the equation dimensionally correct.

This formula provides a good approximation at low frequencies and also at high frequencies if the amplitudes are limited. In [4] has been shown how it fits better the data analyzed than the “power law”, for this reason in this work this formula will be used.

5. DATA, COMPARISON AND DISCUSSION

Nowadays there exist lots of devices that are used to store data, like sensors or computers. Almost every economic activity includes tasks where data is recorded and then saved in computers in databases for one reason or another. These data consists normally in a sort of numbers in the form of vectors or matrices prepared to be analyzed afterwards. Obviously these databases are worthy for the information that can be extracted from them by a proper analysis.

A proper and polite method to work with data would be by following the points below.

- **Recording.** This is the first step of the process. The recording of the data can be done in different ways (e.g. by hand, with sensors, with computers, using electronic devices, etc...) depending on the type of data that is recorded. The quality and precision of the data recorded depends on the recording device used.
- **Preprocessing.** The aim of the preprocessing is to prepare the data in order that can be successfully processed. Here an overall look to the data must be done and big problems like the noise must be depurated. A good example would be a sensor that is broken while it is working but keeps recording zeros or nonsense numbers. These data must be erased.
- **Processing.** Once the data is in a good shape it is time to analyze it. Different algorithms can be applied in the same sort of data depending on the information that is searched or in the precision of each algorithm. Furthermore, it is also possible to apply different algorithms in order to search the same information or parameter.
- **Interpretation and evaluation.** Once the data has been processed, the information obtained must be valued and validated. In the case that multiple algorithms are used to search one parameter, a discussion must be made in order to compare which of the results obtained is more suitable.

The scope of this Master's Thesis is to catch the damping of the vibration of the power line overhead conductors. For that it is necessary to obtain record the data concerning to the vibration of the conductors. In this current work the vibration data is already available and thus it is not necessary to monitor it, but it is important to know how to obtain it and then understand how it is advisable to work with it.

5.1. Description of the data

The data used to perform this Master's Thesis corresponds to real vibration data recorded in the Dead Water Fell (United Kingdom) in June 2007, on an overhead power line dead-end span of 190 m, using acceleration sensors that were installed on the conductors [5]. Specifically, four sensors were used in order to record the vibration of the four different conductors, two conventional AAAC (Aster 228 and

Aster 570) and two z-shaped (Azalee 261 and Azalee 666), see figure 5.1.1. The main properties of each conductor are written in table 5.1.1. On the one hand, for the bigger conductors, acceleration has been recorded in three directions (X, Y, Z). On the other hand, for the smaller ones, acceleration has only been recorded in two directions, vertical and transversal (X, Y).

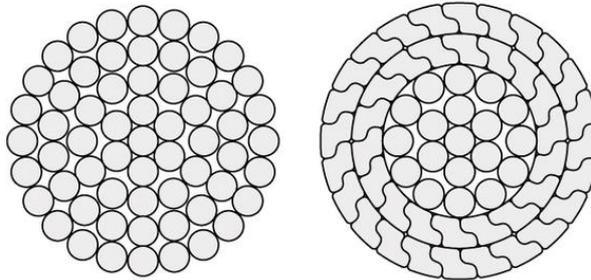


Figure 5.1.1. Section view of two stranded conductors. On the left Aster 570. On the right Azalee 666. (Source: LAMIFIL, July 2013).

Table 5.1.1. Properties of the conductors.

| Name | Aster 228 | Aster 570 | Azalee 666 | Azalee 261 |
|-------------------------|-----------|-----------|------------|------------|
| Area [mm ²] | 227.83 | 570.22 | 666 | 261 |
| Diameter [mm] | 19.6 | 31.05 | 31.5 | 19.6 |
| Breaking load [kN] | 74.05 | 185.3 | 211.6 | 84.9 |
| Linear mass [kg/km] | 648 | 1631 | 1900 | 737 |
| Young's Modulus [GPa] | 57 | 54 | 68.9* | 68.9* |
| Round wires | | | | |
| Wire number | 37 | 61 | 1+6+12 | 1+6 |
| Diameter [mm] | 2.8 | 3.45 | 3.5 | 2.8 |
| Z-shaped wires | | | | |
| Wire number | | | 18+24 | 12+24 |
| Diameter [mm] | | | 3.5 | 2.8 |

(*)The Young's Modulus for the Azalee cables is not available. The value used corresponds to the Young Modulus of the aluminum.

The data recorded corresponds to a period of approximately 550 hours (approximately 396 million elements for each axis direction recorded). The frequency sample of the recording was 200 Hz. Consequently, the data bases are extremely big, and for this reason it must be carefully analyzed. The data bases for each sensor are divided by days, and for each day they are divided in packs of 32768 elements recorded. The records consist in two columns matrices, one column for the acceleration and the other for the time.

One important fact that must be considered is that the tension in the conductors was changed twice during the monitoring of the power line, thus achieving three different levels of tension in the conductors. This is important because tension makes an influence in the self-damping of the cables, and in order to obtain good results the test must be done with different levels of tension. Furthermore, the tension itself also

changes due to other effects, which are the ambient temperature, the effect of the sun and the wind. That is the reason why the data is given in tension ranges. The current would also effect the tension, but in this case there was no current in the conductors. Table 5.1.2. contains the information of the range values for each conductor.

Table 5.1.2. Tension ranges and averages.

| Tensions ranges | Azalee 666 | Aster 570 | Azalee 261 | Aster 228 |
|---------------------------------|-------------------|------------------|-------------------|------------------|
| Tension, range 1 | 27000 N-31000 N | 23000 N-28000 N | 7992 N-10206 N | 8526 N - 9773 N |
| Average Tension, range 1 | 29941 N | 26810 N | 9614 N | 9440 N |
| Tension, range 2 | 31000 N-34000 N | 28000 N-32000 N | 10206 N-12720 N | 9773 N-12127 N |
| Average Tension, range 2 | 32736 N | 29640 N | 11731 N | 11361 N |
| Tension, range 3 | 34000 N-37000 N | 32000 N-36000 N | 12720 N-14687 N | 12127 N-13408 N |
| Average Tension, range 3 | 35500 N | 34000 N | 14350 N | 12700 N |

After the introduction and description of the data samples it would be interesting to think how to understand the data and how to get familiar with it. See the graphics acceleration vs time represented below in figure 5.1.2.

Figure 5.1.2. represents one whole day data. The X-axis corresponds to the time from 0 to 24 hours and the Y-axis corresponds to the acceleration. As it can be observed, in a first look all four cables follow the same pattern of vibration. This is because the wind shape force is almost the same for all the conductors, there are some differences because in the bigger cables the surface of incidence is also bigger, and their mechanical characteristics can influence their vibration.

It can be easily deduced that in that day, during the night hours the vibration is high and irregular, may be due to high turbulences. In the following chapters we will discover that in this period of time aeolian vibrations have happened. On the other hand, during the day hours and the first hours of the following night the vibration is quite regular shaped, with a slight increase.

Finally, weather data is also available, but only the wind speed records have been used to plot figure 7.1.1.2. Databases for the weather recorded data are smaller than the ones for acceleration, because just one element has been registered every 8 seconds during all the 550 hours of records.

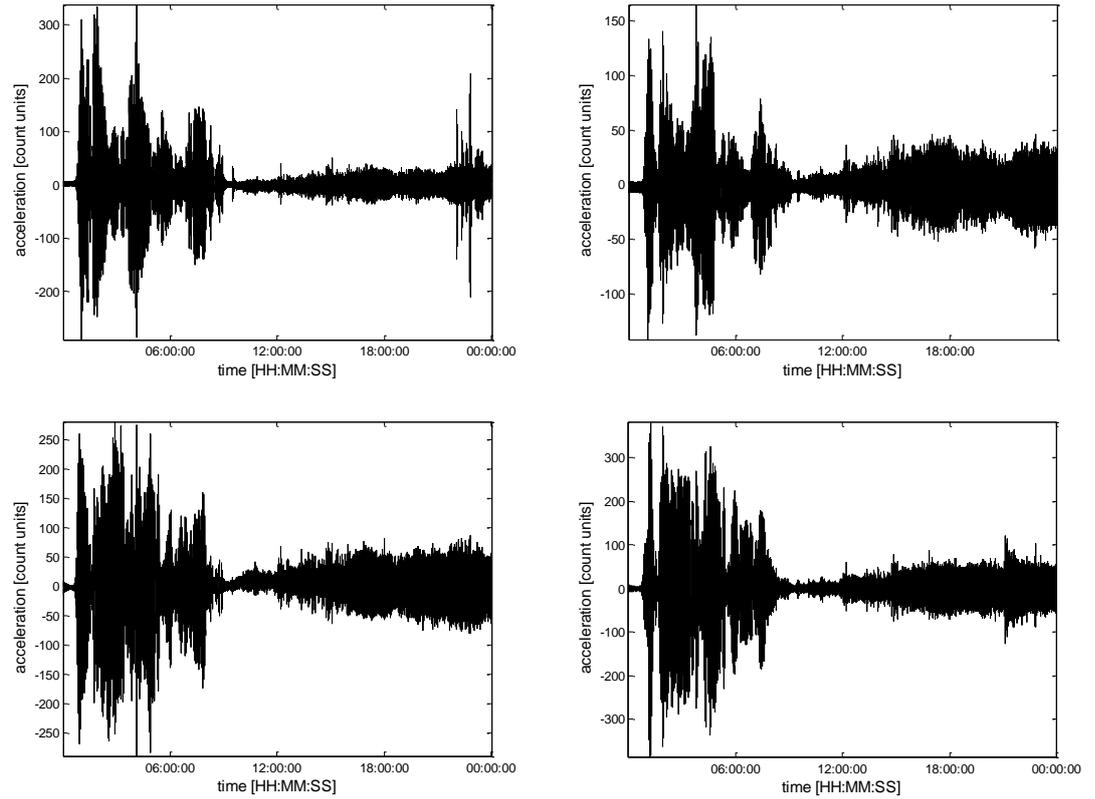


Figure 5.1.2. One day representation Acceleration (axis Y) vs Time. Up: the one on the left corresponds to Aster 228, the one on the right corresponds to Azalee 261. Down: the one on the left corresponds to Aster 570, the one on the right corresponds to Azalee 666.

5.2.Data used

Given that the amount of data available is so big, and also that the main objective of the project is to develop a method to get the damping of the vibration data, only a small part of this data has been used. To be more specific, only one day sample of the Y-axis vibration of the conductor Aster 570 and Azalee 261 have been used.

6. ANALYSIS PROCESS

The process that has been followed to analyze the data is introduced in this chapter. It is divided in two blocks: the preprocessing and the processing of the data.

- Preprocessing

The first step of the preprocessing is to read the acceleration data of one of the sensors in the vertical direction. The raw data is in count units, so a conversion factor must be applied into it in order to transform it to international system units. Afterwards the acceleration is plotted against the time in order to visually detect the possible aeolian vibration events. Once they have been detected, they are analyzed separately, thus it is necessary to obtain the initial and end points of each event.

The next step is to pick one event's data and prepare it to analyze it properly. For this reason it is filtered in order to remove the noise, by means of a mean filter and a median filter. The last step of the preprocessing of the data is to transform it from acceleration to displacement, and this operation is done in the frequency domain.

- Processing

After the preprocessing the displacement data is ready to be analyzed. The tool chosen for that reason has been the Prony's Method, because given an input vibration data it returns the amplitudes, the frequencies and the damping coefficients. The input data has been analyzed in smaller samples, because it does not allow the analysis for big data samples. The outputs have been stored in excel files.

After this simplified introduction of the analysis process, in the following chapters you can find a far deeper and detailed explanation.

7. PREPROCESSING OF THE DATA

In order to do a successful analysis of a data sample it must be preprocessed to adapt it to the analysis. In this chapter the method and techniques used to preprocess the data are explained. The first step followed is an observation of the data, with the scope to detect the Aeolian vibration events. For this reason FFT transforms are applied in order to plot the frequencies spectrum. Then the data which is going to be analyzed (one event) is deperated using a median filter and removing its mean value. Finally the acceleration data is converted to displacement data in the frequency domain.

7.1. Observation of the data

The first step to observe the data is to plot it in the time domain. The main objective to do it is to detect the different aeolian vibration events. In this subchapter it is explained how to do it.

7.1.1. *Detection of Aeolian Vibration*

One important step to do to analyze the data is to detect when the aeolian vibration phenomenon occurs. This is because the data recorded represents the vibration of the overhead conductors, but this vibration can be induced by different causes and it is not always due to aeolian vibration. In this current work it is done by the following way.

First of all, an overall look must be taken to a whole day acceleration data graphic. In there it is possible to find different “episodes” or events of vibration. A particular characteristic of an aeolian vibration event is that they are composed by a growing stage, afterwards a permanent stage and finally a decreasing stage. So it is necessary to split each event with this shape in order to study it separately and determine if the vibration of that event is aeolian. Look figure 7.1.1.1, which represents the raw acceleration data of conductor AZALEE 261 during the 9th June 2007, during 24 hours, which correspond to a data sample of more than 17 million of elements.

In that figure it has just been marked one of the possible events in red, but looking more accurately it can be seen that there exist more than one, mostly in the left half of the graphic. In the right sight of the graphic the acceleration looks constant, so in a first sight it does not seem to exist aeolian vibration. The element marked corresponds to the acceleration monitored between 00:50:55 and 01:29:16 (time in hours:minutes:seconds)

Once one event has been detected, it must be separated of the rest of the data to make a proper analysis. Then, the growing, the steady and the decreasing stage of the event must be studied separately. A fast Fourier transform (FFT) can be applied to the data, and afterwards represent the spectral density in order to see the dominant

frequencies. If the spectral density is condensed in a small number of peaks of frequency, typically between one and three, then it means that that event corresponds to an aeolian vibration phenomenon. This is for the following reason. As it has been explained in the subchapter 2.1. the aeolian vibration has an onset wind velocity V_S that depends on the diameter of the conductor d which produces a vertical vibration in the cable with a frequency f_n (see equation (1)). While the wind velocity remains between $0.9 \cdot V_S$ and $1.3 \cdot V_S$ the frequency of vibration keeps constant because of the lock-in effect. Nevertheless, if there is a substantial change in the wind velocity, another frequency value will be reached. Regarding figure 7.1.1.2., it is clear that this is what has happened here, since the wind speed has been increasing in a more or less uniformly way.

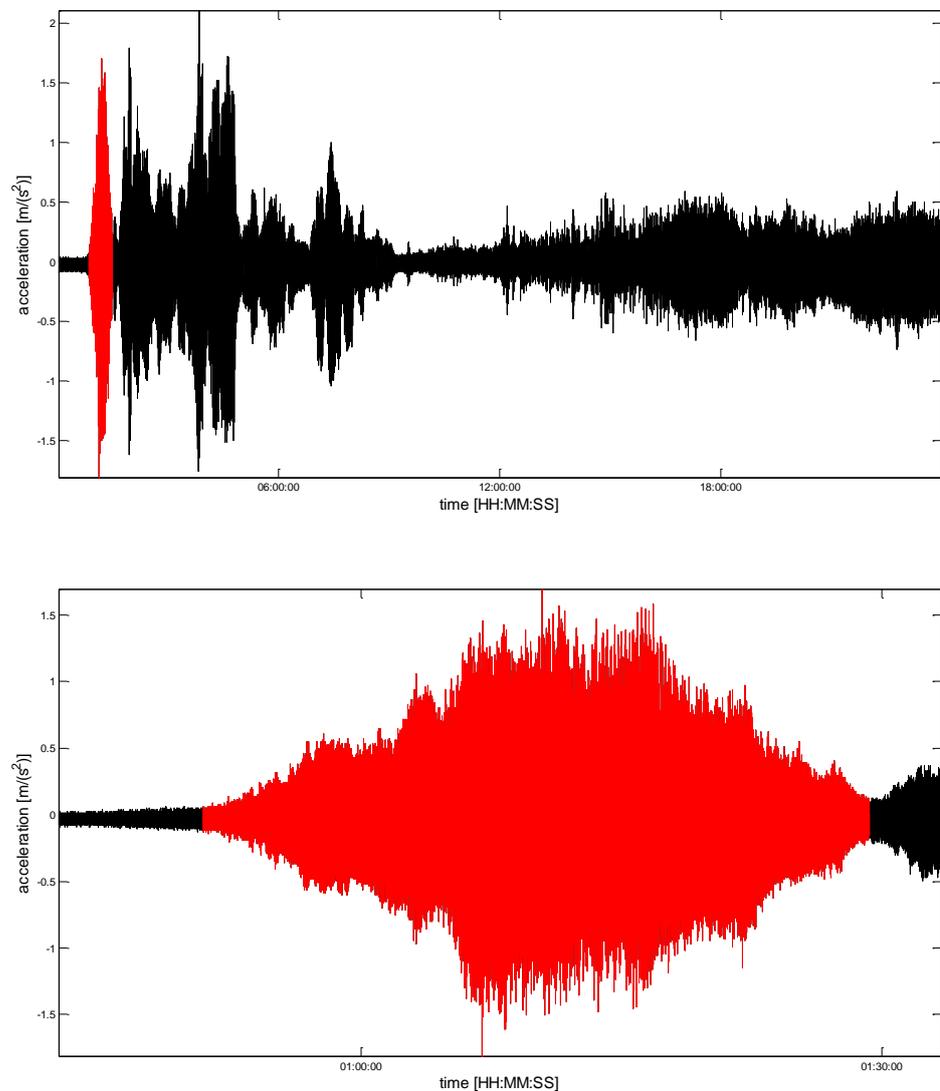


Figure 7.1.1.1. Up: One day acceleration data measurements. One possible aeolian vibration event is plotted in red. Down: zoom of the possible aeolian vibration event (plotted in red).

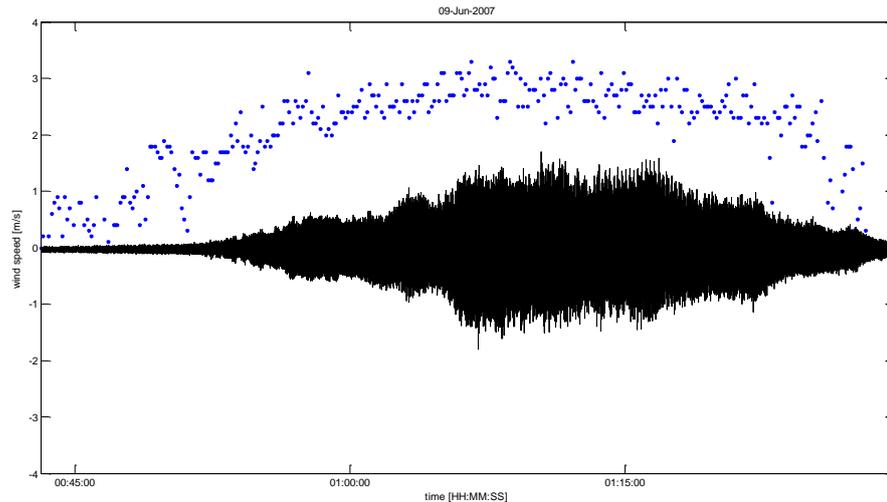


Figure 7.1.1.2. Blue points represent the wind velocity and black lines represent the acceleration data of an aeolian vibration event, both in the same period of time.

A representation of the spectral density for the acceleration of the ascending stage of the first event marked in figure 7.1.1.1. has been done. Look figure 7.1.1.3. It corresponds to the same data and the same period of time period of time represented in figure 7.1.1.2. There you can see as how, indeed, there are only a few remarkable peaks of frequency.

Furthermore, as the data which must be studied in this work corresponds to displacement data, so the corresponding frequency spectra must be studied, too. It is very important to remark the differences between the spectral density for the acceleration and for the displacement. The conversion from acceleration data to displacement data is done in the frequency domain (see section 7.3), dividing the acceleration values by their corresponding frequencies at the power of two ($A(\omega)/\omega^2$). For this reason, some high frequencies which are detected in the acceleration spectrum, are not visible in the displacement spectrum. Moreover, some low frequencies which are not observable in the acceleration spectrum, become visible in the displacement spectrum. To illustrate this take a look to figure 7.1.1.4. The data represented in this figure is the same than in figure 7.1.1.3. but converted to displacement. It can be clearly seen like the maximum peak of the acceleration in 33.95 Hz has “disappeared” in the displacement spectrum. The second peak of acceleration in 19.64 Hz, can be detected in displacement but it is not very remarkable.

One last remarkable point in the displacement spectrum is the huge concentration of spectra in the lowest frequencies. This concentration is due to the noise in acceleration data, which becomes really huge when converting to displacement. For this reason, the data must be filtered. The filtering process is explained in section 7.2.

Figure 7.1.1.5. illustrates another example to better understand this phenomenon. In this case, the displacement data has been filtered. The data corresponds to a

portion of 20 seconds of the same data used to plot the previous figures. The time plotted is between 00:59:16 and 00:59:36 (in hours:minutes:seconds).

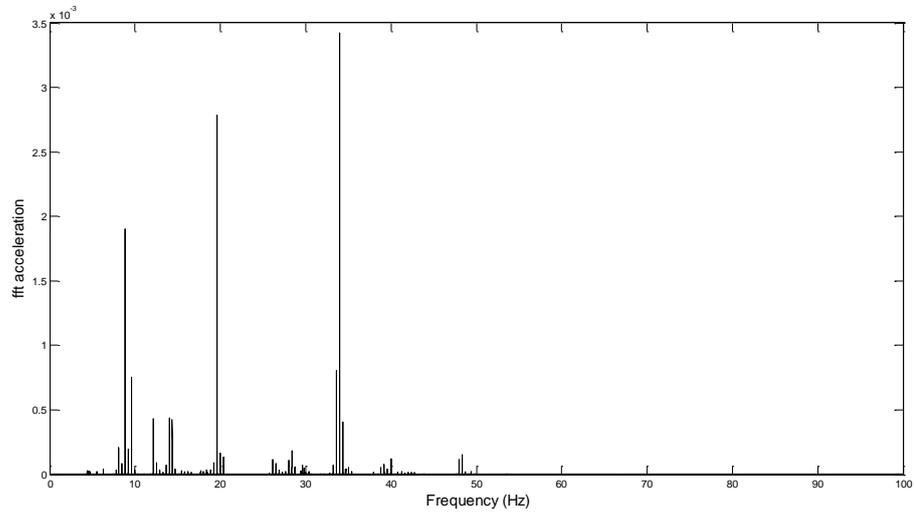


Figure 7.1.1.3. Spectral density of acceleration data corresponding to an aeolian vibration ascending event.

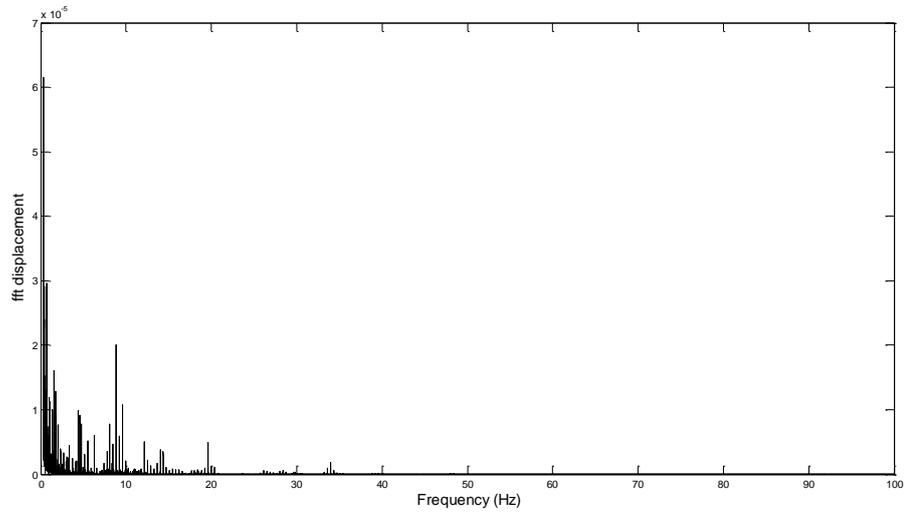


Figure 7.1.1.4. Spectral density of displacement data corresponding to an aeolian vibration ascending event.

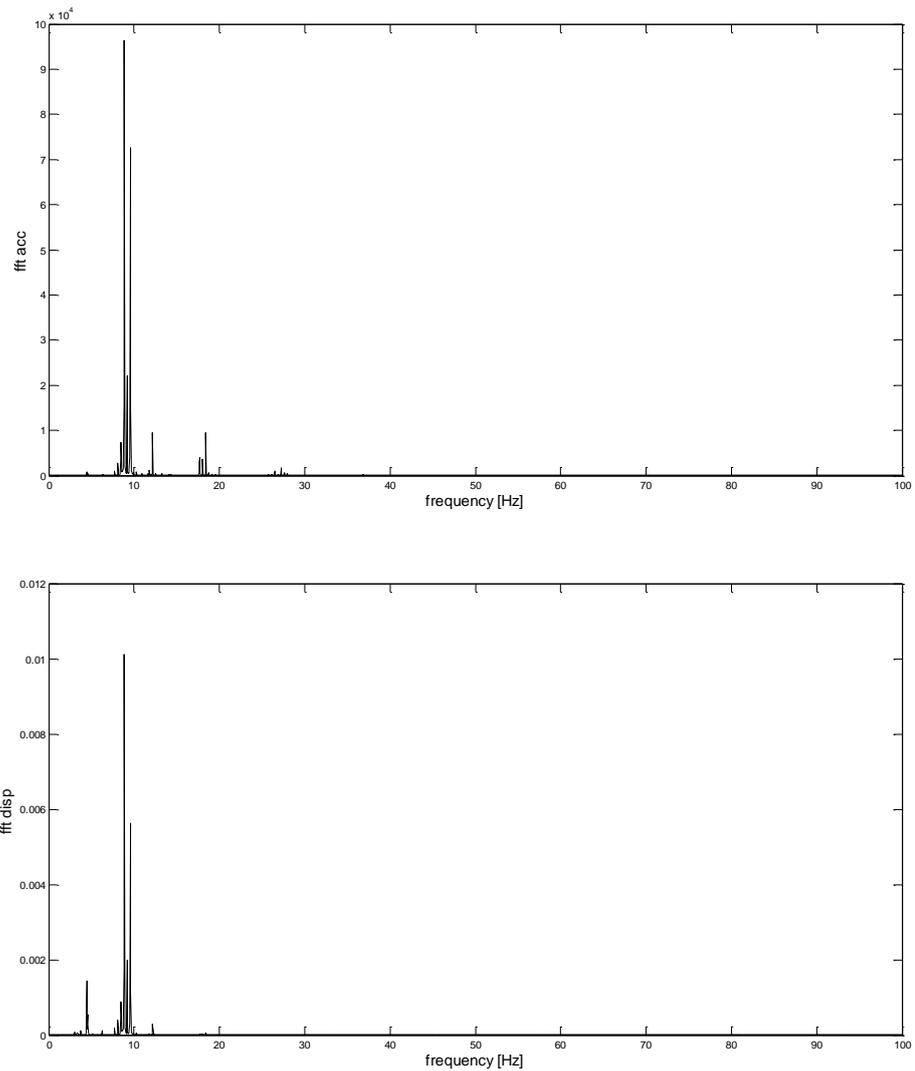


Figure 7.1.1.5. Spectral density of acceleration data (up). Spectral density of displacement data (down).

The observation of the frequency peaks in displacement data is an important step for one next step in the analysis process, because it determines the model order for the Prony's Method application.

7.2. Depuration of the data

When data is recorded with sensors it is always contaminated with noise. The noise is composed by those meaningless values that are registered in the data for different reasons, like exceptional hardware failures, records with no information because the input in the sensor is out of its sensitivity, etc... At the end, the noise can perturb the real information that can be extracted from a data sample, and for this reason it must be depurated.

There exist several different methods to clean or filter the noise, but just two of them have been tested in this project: the median filter and removing of the mean value. Both methods are commonly used in image noise depuration with great success. In the following lines you can find a brief theoretical explanation of how both methods are applied.

7.2.1. Median Filter

The median filter can be applied in several dimensional input signals. Its working methodology is to build and output signal in the following way: it enters one by one to all the positions in the input signal and replaces its value by the median of its neighbors. In the current case, the signal is 1D. So the output in the i^{th} position would be the median of the values in the position $i-1$, i and $i+1$ [6].

7.2.2. Removing Mean Value

To remove the mean value has been done is to calculate the mean of the whole sample analyzed, and subtract it from every single element. In this way the continuous component of the signal is extracted. This is useful because the data sample values should have a mean value of zero, since they represent an oscillatory movement.

As a conclusion, in this present work both filters will be used in order to deperate the noise in data. The median filter has shown to be useful to clean the overpeaks of noise while the mean filter allows to eliminate the continuous component of the signal.

7.3. Conversion from acceleration to displacement

The final goal of this Master's Thesis is to get the damping from the displacement data. For this reason when the data has been depurated it must be transformed from acceleration to displacement. The transformation can be done in the time or the frequency domain. In this case it is easier to do this operation in the frequency domain, because in the time domain it is necessary to integrate the acceleration $a(t)$ in order to obtain the velocity $v(t)$ and afterwards integrate the velocity again to finally obtain the displacement $y(t)$, and this process is more complex to compute.

In the frequency domain the process is much simpler because the transformation can be done directly from acceleration to displacement, without having to calculate the velocity and avoiding the integration that must be done in the time domain. The process that is going to be described is called the Omega Arithmetic Method (OAM) [7]. To apply the process the different frequencies of the signal must be considered separately. Since the data is composed by vibration signals, consider the i^{th} frequency of a given displacement signal $y(t)$.

$$y_i(t) = A_i \cdot \sin(\omega_i \cdot t) \quad (36)$$

Where A_i is the amplitude of the i^{th} frequency of the signal, and $\omega_i = 2 \cdot \pi \cdot f_i$ is the frequency.

To continue with the explanation of the OAM the relationships between acceleration, velocity and displacement must be considered.

$$a(t) = \frac{dv(t)}{dt} \quad (37)$$

$$v(t) = \frac{dy(t)}{dt} \quad (38)$$

The transformation of a signal from the time domain to the frequency domain is done applying the discrete Fourier transform (DFT) to that signal. Furthermore, this transformation is reversible, so it is possible to obtain the expression in the time domain of a signal represented in the frequency domain. This transformation is called inverse Fourier transformation (IDFT). The expressions of the inverse transform for the acceleration, the velocity and the displacement are written below.

$$a(t) = \int_{-\infty}^{+\infty} A(\omega) \cdot e^{j\omega t} d\omega \quad (39)$$

$$v(t) = \int_{-\infty}^{+\infty} V(\omega) \cdot e^{j\omega t} d\omega \quad (40)$$

$$y(t) = \int_{-\infty}^{+\infty} Y(\omega) \cdot e^{j\omega t} d\omega \quad (41)$$

From equations (37) and (40) the following expression can be deduced.

$$\begin{aligned} a(t) &= \frac{d}{dt} \left[\int_{-\infty}^{+\infty} V(\omega) \cdot e^{j\omega t} d\omega \right] = \int_{-\infty}^{+\infty} V(\omega) \cdot \left(\frac{d}{dt} [e^{j\omega t}] \right) d\omega \\ &= \int_{-\infty}^{+\infty} j \cdot \omega \cdot V(\omega) \cdot e^{j\omega t} d\omega \end{aligned} \quad (42)$$

Comparing both expressions (39) and (42) for the acceleration the following is obtained.

$$\int_{-\infty}^{+\infty} A(\omega) \cdot e^{j\omega t} d\omega = \int_{-\infty}^{+\infty} j \cdot \omega \cdot V(\omega) \cdot e^{j\omega t} d\omega \quad (43)$$

So,

$$A(\omega) = j \cdot \omega \cdot V(\omega) \quad (44)$$

The process developed before to obtain the relationship between the acceleration and the velocity in the frequency domain can be repeated to obtain the relationship between the acceleration and the displacement, and also between the velocity and the displacement. The result required in this Master's Thesis is the relation between displacement and acceleration.

$$A(\omega) = -(\omega^2) \cdot Y(\omega) \quad (45)$$

Then, the routine that must be followed to convert the acceleration data to displacement data is described in the following points. It must be considered that the data processing is done with the software MATLAB©.

- The first step is to transform the acceleration data sample, which has been previously filtered, from the time to the frequency domain. For this reason a fast Fourier transform is used instead of the DFT, since it is easier to compute and it gives good results.
- Once the data is in the frequency domain, the displacement can be obtained by dividing the data sample by $-(\omega^2)$.
- The next step is to delete the fundamental component of the resulting signal, because when dividing by $\omega = 0$ it gives an indeterminate result. Since aeolian vibrations are characterized for frequencies between 3 Hz and 200 Hz, the data deleted is all those values under 3 Hz because it is out of the range of interest. Figure 7.3.1. shows how the effect that produces the low frequency values in the integration of the data. The data sample represented in this figure corresponds to the same sample represented in figure 7.1.1.4.
- The last step of the process is to apply the inverse transformation so as to obtain the displacement signal in the time domain. Figure 7.3.1. shows the resulting displacement data obtained.

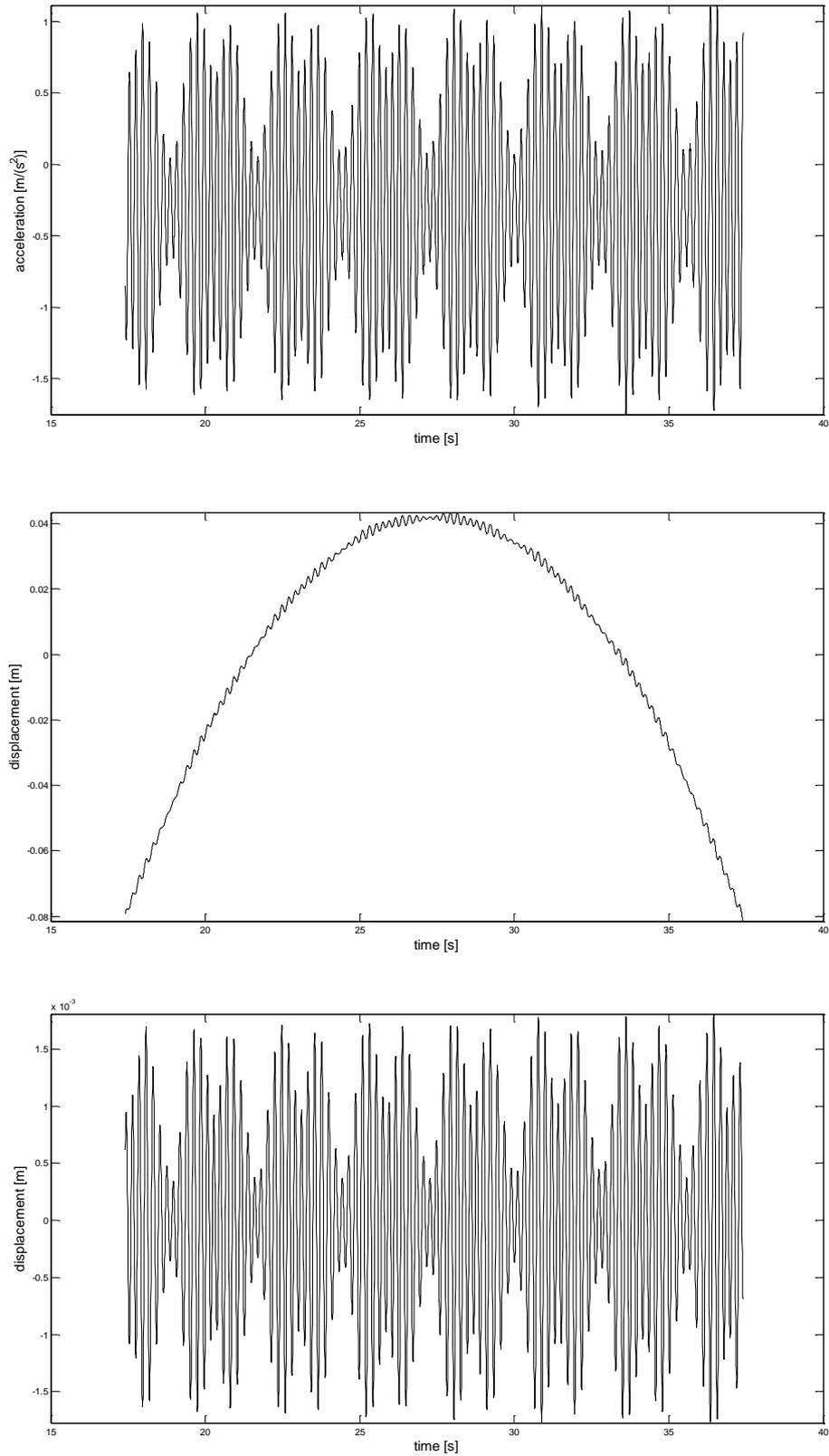


Figure 7.3.1. On the top acceleration data sample. In the middle the displacement obtained without deleting the lower frequencies. Below, the displacement obtained deleting the frequencies under 3 Hz.

8. PROCESSING OF THE DATA

When the data has been preprocessed, it is suitable to analyze it. In this chapter the method used to process the data is explained. The first step is to apply the Prony's method to the chosen data sample. The outputs obtained must be correctly stored in a suitable data base and afterwards the results must be validated.

8.1. The Prony's Method (PM)

The Prony's method is a useful mathematical tool that can be used to obtain the damping of a given data sample or signal for every single frequency. Moreover, one condition to apply the PM is that the data input must be uniformly sampled [8].

The idea of this method is to model a system which output consists of a linear sum of exponentials which fit the input signal $y(t)$ (see equation (46)). As you can see, this is similar to the DFT. Furthermore, its singularity is that it returns the frequency, the amplitude, the phase and also the damping components of the input signal, so it is an advantage in respect to DFT.

$$y(t) = \sum_{i=1}^N A_i e^{\sigma_i t} \cos(2\pi f_i t + \Phi_i) \quad (46)$$

After some mathematical development using the Euler's formula, equation (47) can be expressed as the following.

$$y(t) = \sum_{i=1}^N \frac{1}{2} A_i e^{\pm j\Phi_i} e^{\lambda_i t} \quad (47)$$

This expression permits an easier computation. The meaning of the output variables in the previous equations is found in the table 8.1.1. below.

Table 8.1.1. Output variables in the PM.

| Symbol | Output Variable |
|------------------------------------|---------------------------|
| $\lambda_i = \sigma_i + j\omega_i$ | Eigenvalues of the system |
| σ_i | Damping components |
| Φ_i | Phase components |
| f_i | Frequency components |
| A_i | Amplitude components |

When the PM is used some considerations must be done. First of all, the PM is not a suitable tool to apply in signals contaminated with noise. For this reason the data input must be preprocessed by means of applying a filter to deplete the noise (see subchapter 7.2.). Afterwards, the size of the data input must be also considered in order to obtain a good fitting in the resulting function. Finally, the most important

step of the method is the determination of the order (N) of the model. The order determines how many exponentials compose the output function.

The PM has been applied with the MATLAB[®] which incorporates a tool to compute it. However, this tool has some limitations when the data input format is uncommon. Furthermore, it does not work for large data inputs, so the data must be analyzed in smaller data samples.

8.2.Evaluation of the damping coefficient obtained

Once the analysis of the data has been made, the results obtained must be evaluated in order to do a correct interpretation of them. The results, which come from data measured under different weather and stress conditions, must be referred to a reference case because in this way they can be compared between them. To do it, equation (48) has been used, which is an adaptation of equation (35).

The first step is to define the reference case. The values assigned to each variable can be found in table 8.2.1.

Table 8.2.1. Reference case values for conductor ASTER 570.

| Variable | Value [S.I. units] |
|--------------|--------------------|
| C_* | 1 |
| N_{ref} | 30000 |
| δ | 0.25 |
| y_{maxref} | 0.001 |
| f_{ref} | 10 |

The values are assigned for the following reasons.

- Parameter δ is proposed for an AMS 621 conductor in [9]. Given the difficulty to calculate them, the value proposed is taken as a constant in this work, since they are used successfully in [4] with the same data analyzed in this project.
- C_* is a constant parameter with amplitude 1.
- The tension N_{ref} considered is a round value comprised in the range of the tensions in the conductor analyzed (table 5.1.2.).
- The variable y_{maxref} represents the antinode displacement for frequency f_{ref} . The value considered is in the order of the displacements values of the conductor.
- The value for the frequency of vibration f_{ref} is one in the range of the possible frequencies of the aeolian vibrations.

Once the reference case is defined, the damping results $\frac{1}{\sigma_i}$ obtained with the Prony's Method can be referred to the reference case using equation (48), obtaining $\frac{1}{\sigma_{ref}}$. However, one observation must be done. The variable y_{max} is not easy to

calculate, and its calculation is out of the scope of this Master's Thesis. For this reason, the variable that will be used instead is the one obtained directly from the Prony analysis.

$$\frac{1}{\sigma_{ref}} = \left(C_* \frac{N_{ref}}{N_i} \right)^{\delta + \frac{1}{2}} \left(\frac{y_{maxref}}{y_{maxi}} \right)^3 \left(\frac{f_{ref}}{f_i} \right)^7 \left(\frac{N_i}{N_{ref}} \right)^4 \left(\frac{1}{\sigma_i} \right) \quad (48)$$

8.3. Results storage

Once the analysis of the data has been made, the results must be saved somewhere. A good idea to save them is to create a three-dimension matrix where the different damping coefficients can be stored depending on three different variables, each one representing one of the dimensions. These three variables are the frequency of vibration, the tension of the conductor and another one that could be, for example, the displacement.

It must be considered that one data sample that comprises one aeolian vibration event, can contain more than 200.000 elements. This means that if the order of the system is $N=4$ and the sample is analyzed in packs of 500 elements, more than 800 output values will be obtained. Under the same conditions of amplitude, frequency and tension, the values of the damping coefficient should be similar. Then, the reference matrix could be filled up with the median of the damping coefficients which have been obtained in the same physical conditions. To calculate that median, the anormal values should be extracted.

Analyzing all the data the matrix could be completely filled up. Obviously, there would be one different matrix for each conductor. Then, when analyzing the vibration of that cable, the damping coefficients obtained could be compared with the coefficients of the matrix, and if they are very different it could be an indicator that something is happening in the conductor.

Unfortunately, the results obtained with the analysis using the Prony's Method have not been satisfactory as it is explained in the next chapter. For this reason the matrix has not been written.

9. RESULTS AND DISCUSSION

In this chapter the results obtained are presented and discussed. The database is so extense, the number of elements resulting of the analysis of just one single aeolian vibration event is very extense, too. For this reason, in this chapter only the necessary results to draw the conclusions will be shown.

9.1. Testing Prony Method

Firstly, the method developed has been tested over some invented and well defined functions, in order to check if it works properly. The first function tested, as you can see in equation (49), is composed by two damped exponentials. Since the Prony Method models a sum of complex exponentials, the model order must be twice the number of frequency peaks. For this reason, it has been tested with a model order of $N = 4$, and the data sample has consisted of 241 elements. The outputs obtained with this analysis can be found in table 9.1.1.

$$f(t) = e^{-100t} \cos(2\pi \cdot 400t) + 0.3 \cdot e^{-90t} \cos(2\pi \cdot 2.3 \cdot 400t) \quad (49)$$

Table 9.1.1. Output values for equation (49).

| Frequency | Amplitude | Damping |
|-----------|-----------|---------|
| 920 | 0.3 | -0,011 |
| 400 | 1.0 | -0,010 |

As you can see, the results obtained with the PM fit perfectly the function. Plotting simultaneously the function modeled and the function analyzed on the time and the frequency domain, it can be corroborated. See figure 9.1.1.

A more complex function (equation (50)) has also been tested. As the function before, the data sample consisted of 241 elements, but the model order chosen is $N=8$. In fact, the new function is the same function but adding one continuous and one growing component. Observing the results in table 9.1.2. and the graphics in figure 9.1.2., you can see as the modeled function also fits perfectly the input function.

$$\begin{aligned} f(t) = & e^{-100t} \cos(2\pi \cdot 400t) + 0.3 \cdot e^{-90t} \cos(2\pi \cdot 2.3 \cdot 400t) \\ & + 0.2 \cdot e^{15t} \cos(2\pi \cdot 2 \cdot 400t) \\ & + 0.5 \cdot \sin(2\pi \cdot 1.3 \cdot 400t) \end{aligned} \quad (50)$$

Table 9.1.2. Output values for equation (50).

| Frequency | Amplitude | Damping |
|-----------|-----------|----------|
| 800 | 0.2 | 0,067 |
| 520 | 0.5 | Infinite |
| 920 | 0.3 | -0,011 |
| 400 | 1.0 | -0,010 |

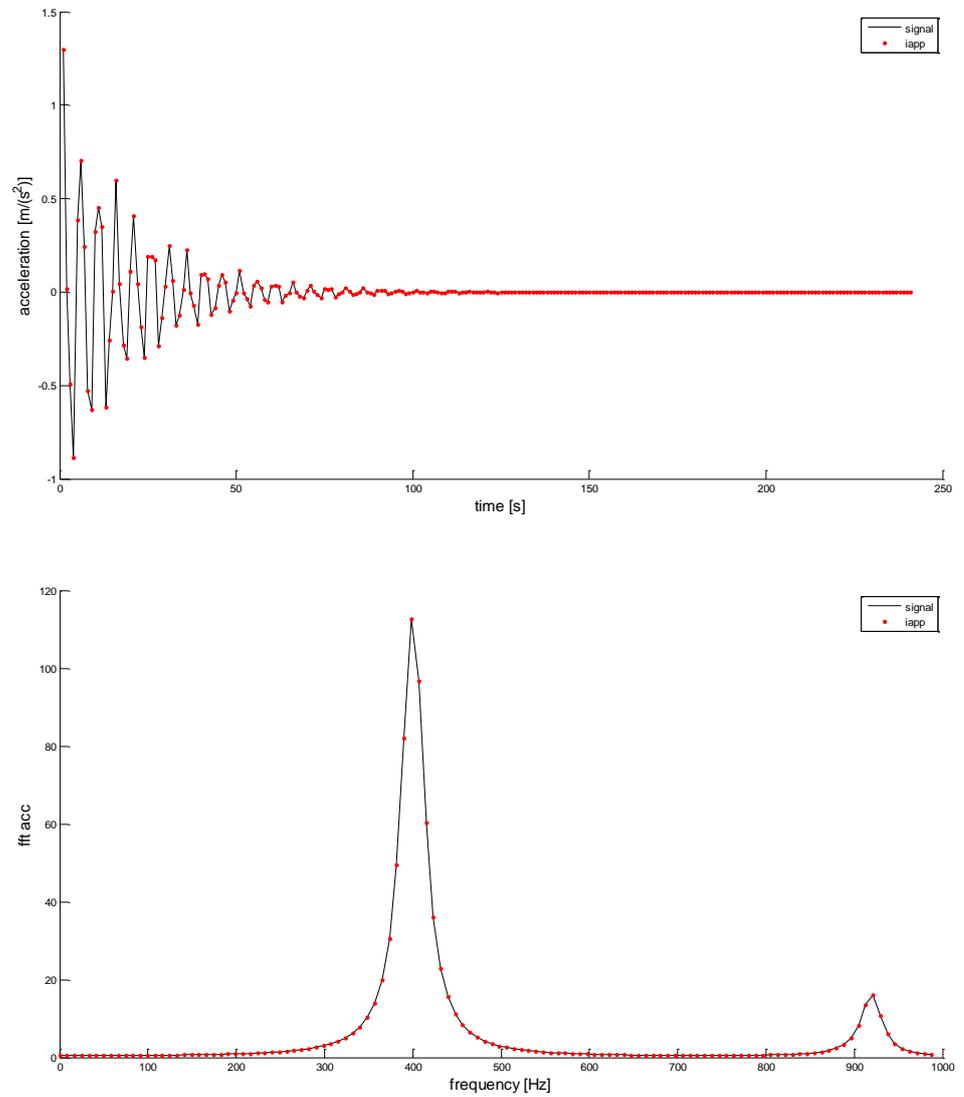


Figure 9.1.1. Raw signal from equation (49) (black line) and the resulting modeled signal using PM (red dots) in the time domain (up) and in the frequency domain (down).

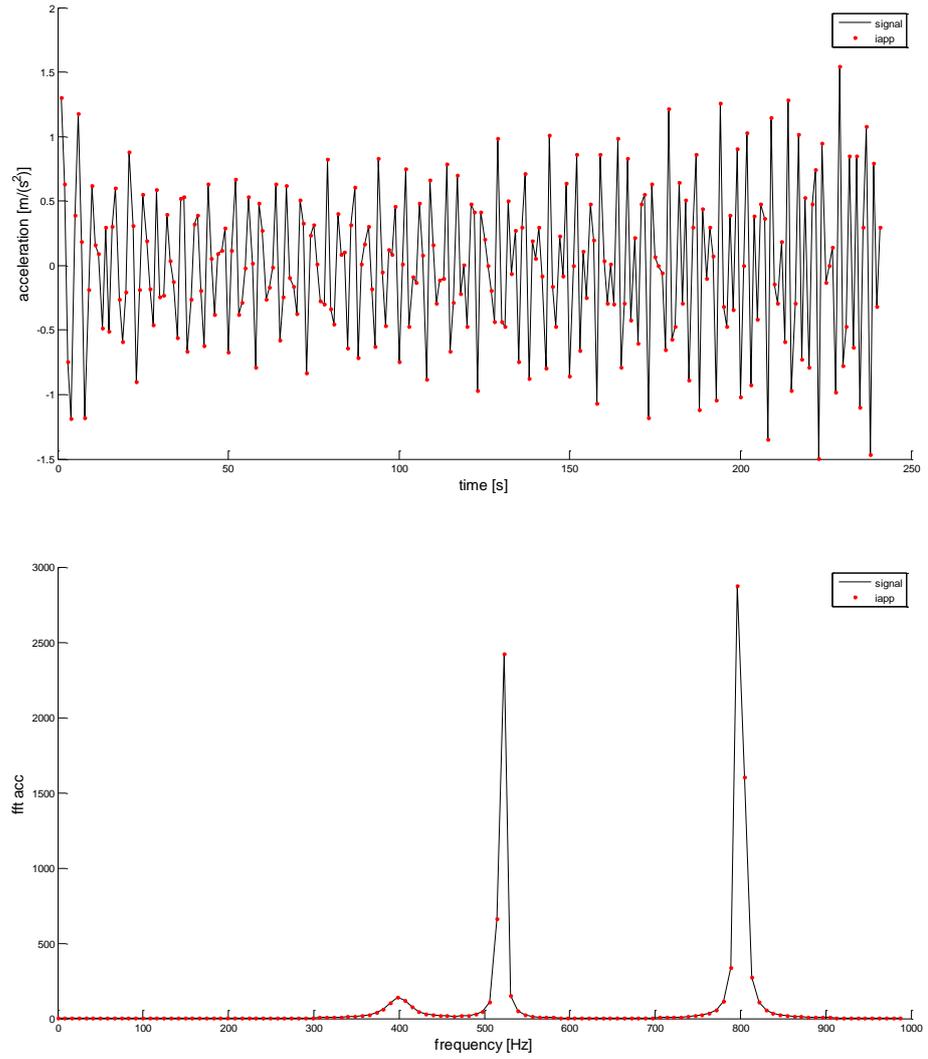


Figure 9.1.2. Raw signal from equation (50) (black line) and the resulting modeled signal using PM (red dots) in the time domain (up) and in the frequency domain (down).

9.2. Analysis of the real data

The results obtained with the analysis of the vibration data have not been successful. This is explained by showing an example of one analysis corresponding to the data sample of growing stage of the first aeolian vibration event of the 9th June of 2007 for the conductor Aster 570. To be more specific, this data sample has a length of 63386 elements, and represents the vibration in time between 00:50:17 and 00:55:33 (time in hours:minutes:seconds). The vibration analyzed corresponds to the vertical acceleration on the axis Y1. All the analysis in this subchapter have been made with a sample frequency $F_s=200$ Hz.

A previous step before doing any of the analysis described in this subchapter is the filtering of the whole acceleration data sample and afterwards the transformation of the acceleration into displacement. In the displacement data the mean value is removed in order to delete the continuous component which appears in the signal.

- Analysis of the whole data sample

The first test realized is an analysis of the whole data sample in a row, dividing the data in smaller samples to be able to apply PM on them using an iteration algorithm. After realizing that this method is not correct, another analysis has been made period by period, watching to the signal spectrum in order to determine the model order. Finally some observations have been done.

First of all, in figure 9.2.1., you can observe the frequency spectrum of the complete data sample, of all the 63386 elements. It is composed by three main peaks of frequency, the biggest in 4.575 Hz, then 4.935 Hz and the other in 3.856 Hz.

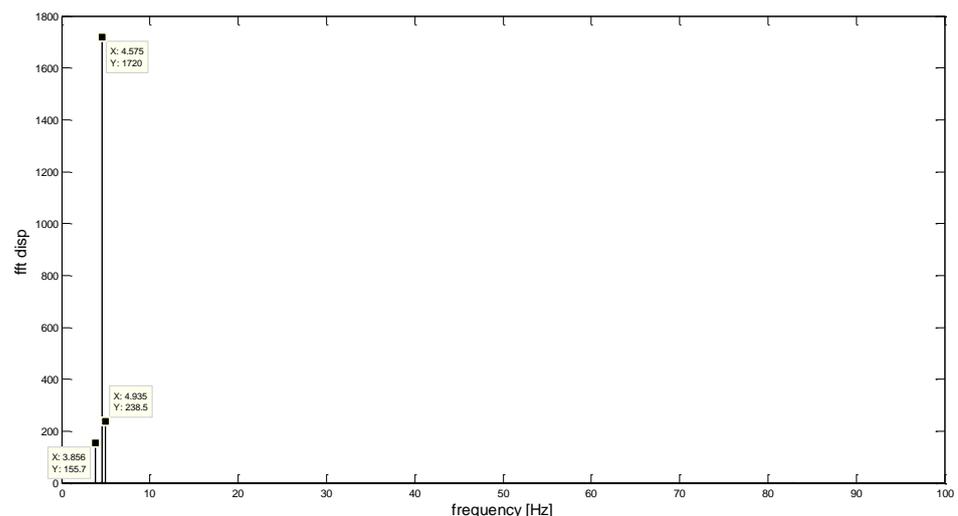


Figure 9.2.1. Displacement's frequency spectrum of the growing stage of the first aeolian vibration event of the 9th June of 2007.

As the signal has three peaks of frequency, it should be analyzed with a model order of $N=6$. The software has limitations and it is not possible to apply the PM to the whole data sample. For this reason the data has been divided in smaller samples, obtaining different results for each sample. The results obtained are very variable and they do not follow any pattern for any sample size tested. So it is not suitable to analyze the whole data sample with the same model order. The analysis must be done period by period, detecting how many frequency peaks appear for each period in order to determine the correct model order.

- Analysis period by period

As mentioned in previous paragraph, the analysis must be done period by period, in order to determine well the model order. This has been tested with the same data used in the previous paragraphs, but only using the first 1000 elements, which correspond to the first 5 seconds of the aeolian vibration ascending event. These 1000 elements have been divided in samples of 500 elements (2.5 seconds), which have been studied separately. Only this amount of data has been used because it is enough to draw the first conclusions.

The first step to apply the analysis method is to plot the frequency spectrum. This will enable the determination of the model order, by counting the peaks of frequency which appear on the plot. See figure 9.2.2., which corresponds to the first sample. One peak of frequency is observable, in 4.4 Hz, so the model order used in this sample when applying PM is $N=2$. Once PM is applied, the outputs obtained are registered in table 9.2.1.

As you can see, the damping obtained is 3.8468, a positive value, which means that the modeled data will increase its value. This is not physically possible, since the self-damping of a conductor represents its energy dissipation, and in this case it would mean that the conductor is absorbing energy, instead of dissipating it. In figure 9.2.3. the modeled signal and the real signal are plotted. You can see that the modeled data has an increasing tendency and that it does not fit at all the real data shape.

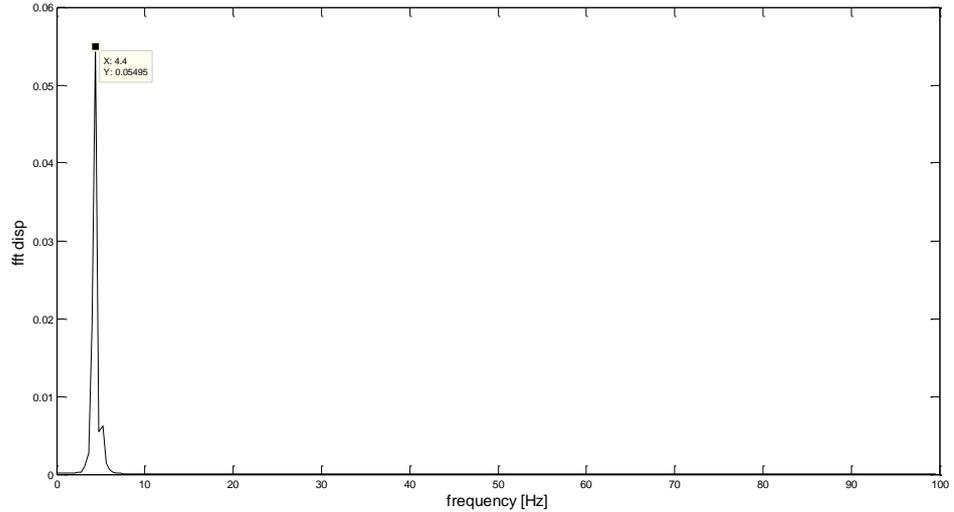


Figure 9.2.2. Displacement's frequency spectrum of the first sample in the analysis period by period.

Table 9.2.1. Output values for the first sample in the analysis period by period

| Frequency (Hz) | Amplitude (mm) | Damping |
|----------------|----------------|---------|
| 4.4778 | 0.6932 | 3.8468 |

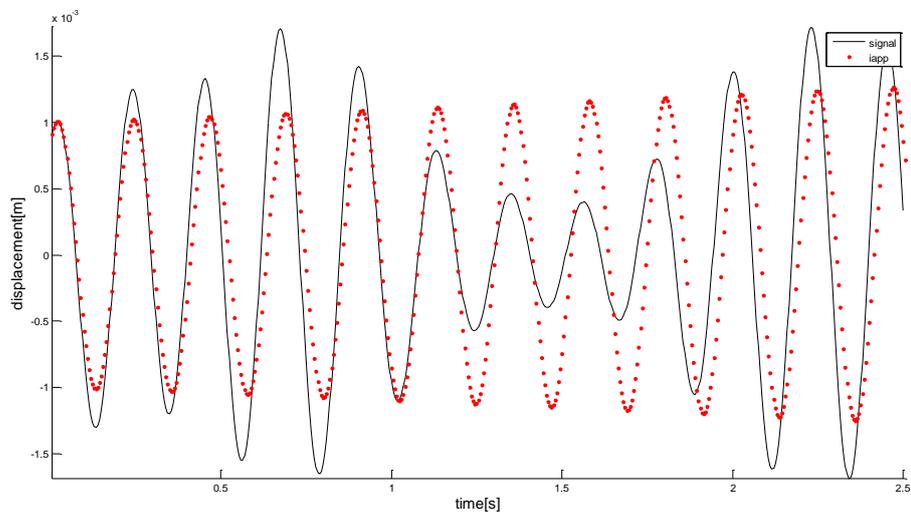


Figure 9.2.3. Displacement (black line) and the resulting modeled signal (red dots) using PM in the time domain.

The next data sample has been modeled with an order of $N=4$, because the signal has two peaks of frequency as it can be observable in figure 9.2.4. The biggest peak corresponds to a frequency of 4.4 Hz, the second peak corresponds to a frequency of 3.6 Hz. The outputs obtained can be consulted in table 9.2.2. The damping values obtained are physically possible, because they are negative, but the frequency

components are not the expected, because they have a continuous component in 0 Hz when the original signal has been filtered eliminating them. In figure 9.2.5. it can be seen as the modeled signal does not fit the original data.

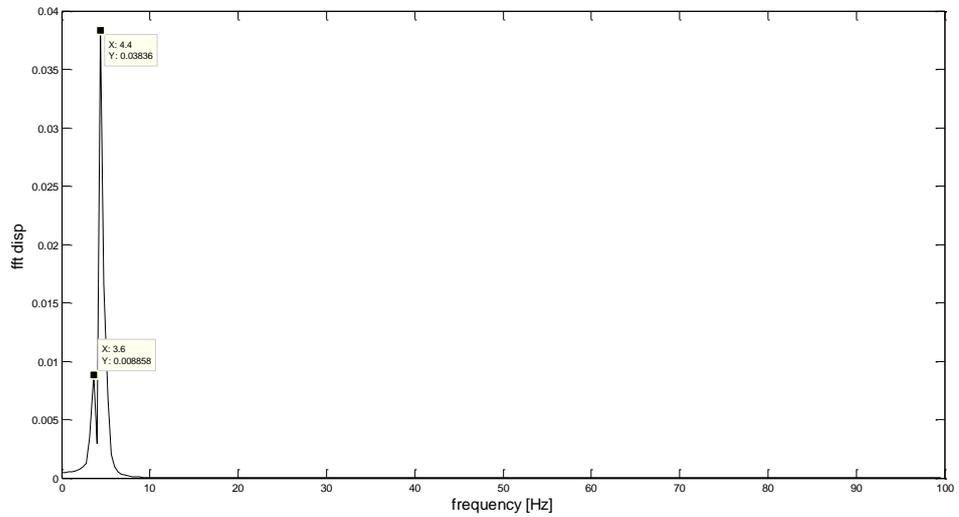


Figure 9.2.4. Displacement's frequency spectrum of the second sample in the analysis period by period.

Table 9.2.2. Output values for the second sample in the analysis period by period

| Frequency (Hz) | Amplitude (mm) | Damping |
|----------------|----------------|---------|
| 4.5452 | 1.506 | -29.01 |
| 0 | 0.1546 | -0.0723 |

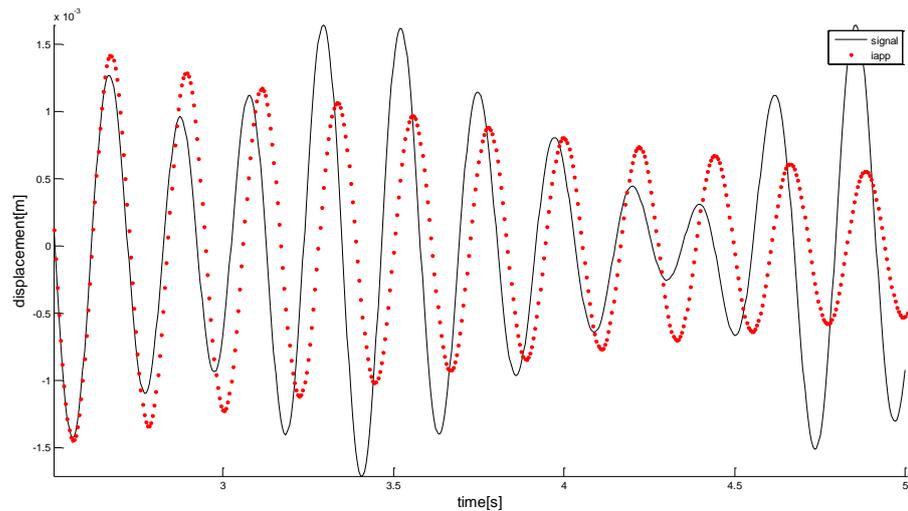


Figure 9.2.5. Displacement (black line) and the resulting modeled signal (red dots) using PM in the time domain.

As the output values show frequency spectra in 0 Hz, another test has been done on the same sample of data. The mean value of the smaller sample has also been removed (in the other analysis the mean value has only been removed in the big sample, before dividing the data in smaller data samples). The results obtained are very close and similar, except for the damping. See table 9.2.3.

Table 9.2.3. Output values for the second sample in the analysis period by period.

| Frequency (Hz) | Amplitude (mm) | Damping |
|---------------------------|---------------------------|----------------|
| 4.5234 | 1.503 | -2.417 |
| 0 | 0.1752 | -0.0894 |

- Observations

Regarding figures 9.2.3. and 9.2.5., one observation done is that, when using PM, the modeled signal tries to fit the first component of the wave that it finds. It can be seen as the modeled signal fits also perfectly the first peak of the signal and that it tries to fit the second peak, but the successive peaks do not really make a big influence on the modeled signal. So for example, in figure 9.2.3., the first peaks have an increasing tendency, for this reason the modeled signal also has an increasing tendency which derives in a positive damping coefficient. On the contrary, figure 9.2.5. has a decreasing tendency on the first peaks, so the damping coefficient obtained in the modeled signal is negative.

- Model with higher order

There is an alternative to try that the modeled function could fit better the input signal. This is by increasing the model order. It has been proved that the determination of the model order is a key point when applying PM. Some authors recommend as a rule of thumb to determine the model order as a third part of the data sample size p.31 [8]. It has been tested in the same data sample previously analyzed, but with a bigger number of elements, corresponding to the first 3000 elements of the sample, which are 15 seconds of data. The bigger the sample is, the better the results that should be obtained according to [8], since the output model fits better the reality. The model order is $N = 1000$. The resulting model is plotted with the input signal in figure 9.2.6.

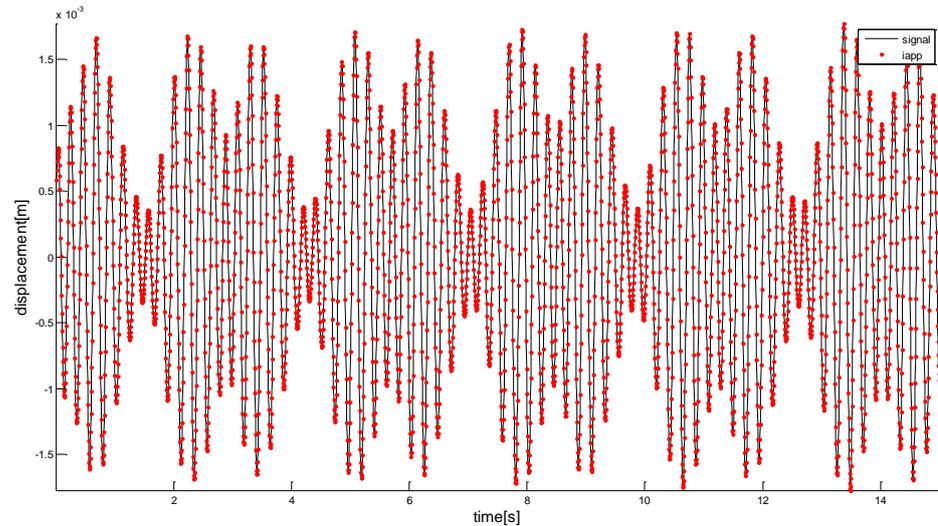


Figure 9.2.6. Displacement (black line) and the resulting modeled signal (red dots) using PM in the time domain.

The outputs values obtained are not written here because there are 500 different outputs for frequency, amplitude and damping. Looking at the results, you can see as they are nonsense. The maximum value obtained is of the order of $3 \mu\text{m}$, for a frequency value of 46.32 Hz. For the frequencies found around 4.6 Hz (closed to the natural frequency of vibration of the conductor) the values of the amplitude can be considered also 0. In table 9.2.4. you can see the results obtained for the frequencies near to 4.6 Hz. Positive damping is not possible, too.

Table 9.2.4. Output values near the modal frequency for case 3.

| Frequency (Hz) | Amplitude (mm) | Damping |
|----------------|----------------|----------|
| 4,9332 | 8,84413E-46 | 158,9078 |
| 4,5733 | 5,47373E-46 | 595,4657 |
| 4,5666 | 2,46812E-50 | -3,0863 |
| 4,4255 | 1,72004E-50 | -1,7642 |

The values obtained with PM for the damping have not been referenced to the reference case because it has no sense to do it when the results obtained are not suitable. So using this high model order is not correct, because you obtain a “copy” of the input signal made with a sum of exponentials, but there are as many exponentials that the results are not physically correct.

- Conclusion

To conclude with, when using PM with a low model order, the modeled signal does not fit well to the input signal. Furthermore, then the model order is high, even when the resulting function plotted fits well the input signal, the numerical results

obtained are neither good. So as a conclusion, PM is not a good tool to monitor the self-damping coefficient of an overhead power line conductor.

10.CONCLUSIONS

In this Master's Thesis the techniques used for the ambient vibration monitoring and how they can be applied to the overhead power line conductors have been introduced. Afterwards the Aeolian vibration phenomenon has been briefly explained. This work is basically focused in the study of the self-damping in conductors, so some theory explaining the damping effect and how to measure the self-damping in conductors (in laboratories) has been introduced, too.

The main objective has been to find a method which could successfully find the self-damping coefficient of the vibration of a conductor. For that purpose real acceleration data has been used. It has been explained how to work with the data, and how to correctly preprocess and process the data. In the process of the data, the Prony's Method has been used to find damping coefficients. This method enables to model an output signal composed by a sum of different complex exponentials, so the frequency components and their corresponding amplitudes and damping coefficients are obtained from a given input data sample.

It can be concluded that the most important step to apply the PM is the determination of its order, which can be done looking at the frequency spectra of the signal and counting how many frequency peaks are there. Furthermore, the most suitable way to work with the data is by dividing it in small samples and analyze it period by period. Unfortunately the damping values obtained with the PM have not been successful, since some of the outputs obtained resulted in positive damping coefficients. In addition, it has been showed how the modeled signal obtained with PM does not fit the original signal.

11.RECOMMENDATIONS FOR FURTHER WORK

It has been proved that the Prony's Method is not suitable to find the self-damping coefficient for the vibration data of overhead power line's cables. For this reason, one suggestion would be to test alternative methods to find the self-damping coefficient. This can be done using the same process used in this thesis to work with the data. That is to say, to do the same preprocessing and processing of the data, but only changing the method applied to find the coefficient.

Once a method gives good results, it would be suitable to find other methods and compare the results obtained between them. Then other criteria to choose one method or another could be evaluated, like the speed of the analysis or the complexity of using those methods.

It would be suitable to consider that when transforming acceleration data to displacement data, high frequency peaks detected in acceleration data may disappear. Those peaks should be detected and studied separately because some valuable information may be hidden there. In this work only the low frequency peaks has been studied.

Finally it could be also very useful to develop a graphical interface which enables to choose which input data are you going to analyze (size of cable, sensor used, axis vibration), which outputs do you want (graphics, tables), etc...

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