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Numerical Method for Evaluating the Dynamic Behaviour of Power Line Conductors: A Global Approach for Pure Bending

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***Abstract*—Transverse vibration of power line conductors under pure bending conditions was developed and modelled using the finite elements analysis (FEA) tool. The finite element model was used to investigate the effect of varying the conductor stringing axial tensions on its dynamic characteristics. The developed numerical method was implemented in MATLAB using the properties for the conductor with code-name TERN. Transient simulations were performed and used to determine the conductors' mode shapes, natural frequencies and damping. Calculated results and experimental measurements were compared and discussed.**

Keywords: ***Wind-induced vibration, finite-element model, numerical method, natural frequencies, self-damping.***

I. INTRODUCTION

The dynamic behaviour of transmission line conductors has been a subject of interest to the design of power lines. This phenomenon occurs due to the aerodynamic effects, generating vortex shedding. The vortex shedding induces a transverse displacement that is perpendicular to the plane of the wind direction. The conductors' response to this aerodynamic effect is non-linear. Due to this phenomenon, the excitation of conductors when subjected to dynamic forces is still not completely understood. Thus, ongoing investigations by researchers are of vital importance in order to improve on the understanding of mechanical oscillations of conductors.

Since conductors vibration was observed on power lines, conscious effort have been made by researchers to model this phenomenon and early investigation can be found in [1, 2]. The earliest mathematical model was developed by R. Claren and G. Diana [3], they developed the mathematical model using the concept of the conductor's principal modes to describe the transverse vibration of a suspended conductor with small sag, tensioned at both ends. Other aspect of the conductor vibration seemed to be studied by researchers and details of concepts and aspects of investigation can be found in [4-10]. Most of these models were developed with the assumptions that the conductors were considered to be a continuous structure subjected to either distributed or concentrated forces. From [4], it was ascertained that modelling a conductor as a beam was more accurate than modelling it as a taut string due to the effect of the bending stiffness.

Some researchers have employed the numerical tool such as finite element method to analyze the dynamic response of conductors. In [11, 12] the authors carried out the finite analysis of conductor. These finite element method FEM was implemented in commercial finite element software packages. In these software libraries, the beam element used to implement conductor dynamic response. Due to the rigorous process of evaluating the conductor self-damping, the implementation becomes a challenge. There arise a need for a customized process to analyze the self-damping parameters.

The power line conductors can be described by a nonlinear partial differential equation as a function of parameters such as deformation, stress-strain relations and damping. This paper presents the finite element analysis of power line conductor using the global discretization approach to characterize its damping capability. This discretization approach uses the deformed beam element to model transverse vibration of conductor as function of its sag due to gravity. The developed numerical model for conductors is used to simulate the dynamic response of the conductors. The simulation was done for Aeolian vibration. This model is used to obtain the conductor natural frequencies, mode shape and also to evaluate the conductor self-damping.

2. MODELING APPROACH

The conductor can be treated either as a continuous distributed parameter system, as a discrete set of concentric orthotropic cylinders i.e. the individual layer of wires is replaced by an equivalent cylindrical orthotropic sheet or as an arrangement of helically curved rods, assembled as a bundle. Analytical modeling was done with different assumptions about the conductor geometry or the inter-strands contacts, with respect to approach applied by the author(s).

In modeling a power line, depending on the parameters of interest usually determine the modeling approach to be used. Also, the degree of accuracy and the ease of linearizing the equation in achieving the set objectives influenced the

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approach adopted. The approach that can be used for the analytical modeling of conductors. They are:

- The Global Approach
- The Local Approach

2.1 The Global Approach

The global approach has proofed to be sufficiently accurate for cases where conductors' parameters are assumed to be distributed under relatively high stress and small displacement. In this condition, the solution of the equation used to model the system is of global interest. This is achieved by employing either a straight or catenary profile of a distributed system to model the geometry of conductor. The solid beam or the taut string model is used for the conductor analytical modeling. In this approach, the global phenomena that are of interest are the natural frequencies, mode shapes, damper placements, loop lengths, wave speed etc.

2.2 The Local Approach

The local approach is implemented, where the conductor is model as a discrete element of an assembly of strands. This approach tends to treat the conductor as a composite structure rather than a continuous distributed structure. The conductor is treated as a composite structure formed by the assembly of helical strands in various layers over the core. This approach make it possible to analyze for the conductor, the inter-strand point contact areas, the effects of friction and the stick-slip regimes during the periodic motion. This approach gives a more accurate representation and results for the conductor. Because the formulation of the equation for strands element yield complex expressions, it used when a higher level of accuracy is required.

3. STATIC PROFILE

The single span of a transmission line conductor can be described by a set of parabolic or hyperbolic functions to describe the deformed shape curves as shown in fig.1. Under the static condition, the conductor is deformed due to gravity; the conductor assumes a centenary profile by sagging along the span. The conductor shape can be described by a parabola or centenary curves. In analysis, a parabolic curve is the shape that is formed by a conductor support by an evenly distributed horizontal weight whereas a catenary is the shape that is formed by a hanging the conductor whose weight is constant per unit of the arc length.

The hyperbolic or the centenary curve equations produce accurate results, but the mathematical formulae which are derivations for the parabola are much simpler with very good accuracy. The parabolic equations were used in this study. Consider a conductor attached to two fixed points A and B and supporting it weight. Assume the conductor between AB carries its weight, uniformly distributed along the horizontal. If w denote the weight per unit length expressed in N/m.

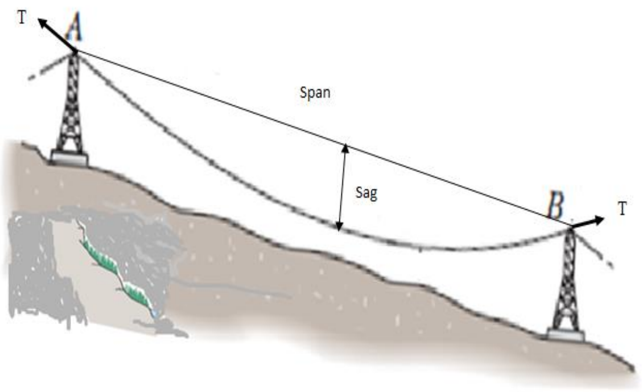

Fig 1: The Conductor Static Profile

Applying the equation of a parabola to a span of the same elevation, with a vertical axis and it's vertex at the origin of coordinates located at point A. The curve formed by the conductor loaded uniformly along the horizontal is modelled as:

$$y(x) = \frac{wx^2}{2H} \quad S = \frac{wL^2}{8T} \quad \tan\theta = \frac{wx}{T_0} \tag{1}$$

Where S = mid-span sag (m), w = conductor weight (N/m), L = horizontal span length (AB), (m), T = conductor tension (N). The sag equations for the power lines strung for cases were the power line passes non-level and mountainous terrain can be found in [13].

4. ANLYTICAL MODEL

Most researches that are conducted to investigate the phenomenon of conductor transverse vibrations, model the conductor either as taut string or beam. The vibrating conductors are modeled as a simply supported beam with sectional parameter such as stiffness, variable linear density, area, and section modulus, subjected to either point or distributed loading. Modelling the conductor as a simply supported beam, the equation of motion of the conductor with axial loading (tensioned at both ends) as described in [3-10] is given as

$$EI\frac{\partial^4 y(x,t)}{\partial x^4} - S\frac{\partial^2 y(x,t)}{\partial x^2} + \rho A\frac{\partial^2 y(x,t)}{\partial t^2} = f(x,t) \tag{2}$$

Where *EI* is the flexural rigidity or bending stiffness, S is the tension, ρ is the density, y (x, t) is transverse displacement, and A is the cross-sectional area.

f (x, t) is the external force, defined as:

$$f(x,t) = F\sin\omega_d t$$

Let $y(x,t) = X(x)e^{-i\omega t}$ $\quad i = \sqrt{-1}$

The homogenous part of the equation is modelled as:

$$EI\frac{\partial^4 y(x,t)}{\partial x^4} - S\frac{\partial^2 y(x,t)}{\partial x^2} + \rho A\frac{\partial^2 y(x,t)}{\partial t^2} = 0$$

Boundary conditions:

$y(0,t) = \frac{\partial y(0,t)}{\partial x} = 0$, at x = 0

$y(l,t) = \frac{\partial y(l,t)}{\partial x} = 0$, at x = l

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Initial conditions:

$$y(x,0) = y_0(x) \quad \text{at x = 0}$$

$$\frac{\partial(x,0)}{\partial t} = \dot{y}_0(x) \quad \text{at x = 0}$$

The natural frequencies, is determined by finding the solution to equation (2) assuming that the mode shape is the same as the pinned-pinned eigenfunction with no external force. The mode shape is expressed as:

$$Y(x,t) = \sin\frac{n\pi x}{l}\cos\omega_n t \tag{3}$$

The natural frequencies becomes

$$\omega_n^2 = \left(\frac{n\pi}{l}\right)^2 \frac{S}{A\rho} + \left(\frac{n\pi}{l}\right)^4 \frac{EI}{A\rho} \tag{4}$$

In [14], it was inferred that to improve on this conductor models, some form of non-linear concepts should be introduced when modelling the conductor dynamic behaviour. The mechanical oscillation of conductors is characterized by non-linearity either from its geometry or damping. In the case of Aeolian vibration, because of the small displacement, the non-linearity is mostly attributed to its damping mechanism.

Based on the work of C. Hardy [15], when the conductor flexes, the strands of the conductor slip against each other; this relative motion generates frictional forces that provide damping. Also, conductors can damp out energy by internal energy losses at microscopic (molecular) level within the core and individual strands of the conductor this is known as metallurgical or material damping. The combination of these energy dissipative processes by a conductor is known as the conductor self-damping. During bending, the energy dissipation due to frictional effects around the area of contacts induced by the sinusoidal forcing function coupled with the material damping tends to limit the amplitude of vibration.

Consider the conductor as visco-elastic beam with the two forms damping as explained in [14]. If the conductor obeys the stress-strain relationship given as:

$$\sigma = E\varepsilon + \beta\frac{\partial\varepsilon}{\partial t}$$

Hence the equation of motion for the transverse vibration of the conductor is expressed as

$$EI\frac{\partial^4 y(x,t)}{\partial x^4} - S\frac{\partial^2 y(x,t)}{\partial x^2} + \beta I\frac{\partial^5 y(x,t)}{\partial x^4 \partial t} + C\frac{\partial y(x,t)}{\partial t} + \rho A\frac{\partial^2 y(x,t)}{\partial t^2} = f(x,t) \tag{5}$$

Using the Rayleigh Method, the above damped nonlinear equation for the conductor, the damping coefficient is obtained as

$$\varsigma_n = \frac{\int_0^l \left(\beta EI(x)\left[X''_n(x)\right]^2 dx + C\left[X_n^2(x)\right]^2 dx\right)}{2\int_0^l \rho A(x) X_n^2(x)dx}$$

5. FINITE ELEMENT METHOD

The finite element method is a very efficient numerical tool for the evaluation of dynamic systems problems such power line Aeolian vibration. This method is a computational technique that can be employed to evaluate the dynamics of systems. Though, a conductor is continuous system but to analyse the transverses vibration using the FEA method involves discretizing the system into its finite elements. The equations are obtained for each finite element. The assembling of these finite element equations results to the global equations that can be used to generate the equations for the inertial, stiffness, applied and damping forces in matrices and vector form. In system dynamics, the mass, stiffness and damping matrices of the system are required to solve the required dynamic response. The dynamic parameters are determined through the use of the classical beam model.

4.1 Finite Elements

The FEA for the conductor formulation is done with the finite element formulation for the beam as shown fig 2. In this method the space dimension was approximated by the higher-order approximation finite element basis function (cubic polynomial) with respect to time i.e. cubic Hermits polynomial. To this regard, the finite element interpolation functions as time dependent such that *u* is approximated by:

$$u = \sum_{i=1} c_i N_i \quad = c_1 x^3 + c_2 x^2 + c_3 x + c_4 \tag{6a}$$

$$u(x) = N_1(x)u_1 + N_2(x)\theta_1 + N_3(x)u_2 + N_4(x)\theta_2 \tag{6b}$$

Where

$$N_1(x) = 1 - \frac{3x^2}{L^2} + \frac{2x^3}{L^3},\; N_2(x) = x - \frac{2x^2}{L} + \frac{x^3}{L^2}\; N_3(x) = \frac{3x^2}{L^2} - \frac{2x^3}{L^3},$$

$$N_4(x) = -\frac{x^2}{L} + \frac{x^3}{L^2}$$

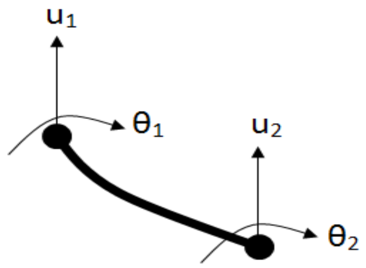

Fig 2: Beam Element

Thus if $[N] = [N_1, N_2, N_3, N_4]$ (7a)

Then $[A] = [N_1', N_2', N_3', N_4']$ (7b)

$[B] = [N_1'', N_2'', N_3'', N_4'']$ (7c)

4.2 Finite Element Formulations

Some physical phenomena can be described by differential equation that relates certain quantities to their derivatives with respect to time and space variables. The weak formulation is used to derive the finite element equation and this is obtained from the equation of motion describing conductor vibration. The Galerkin's method (method of weighted residual), using the differential equation, is used to develop the finite element formulation for the conductor. By applying the Galerkin's variational principle to the time dependent problems, considering the boundaries conditions,

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the finite element model is obtained. Hence, damped equation (5) for the transverse vibration of the conductor is used for this finite element formulation. The weak formulation for the finite element equation is obtained by multiplying equation (5) by the finite element interpolation functions defined by equation (6) to obtain:

$$\int_0^l \left(EI\frac{\partial^4 y}{\partial x^4}u - S\frac{\partial^2 y}{\partial x^2}u + \beta.I\frac{\partial^5 y}{\partial x^4 \partial t}u + C\frac{\partial y}{\partial t}u + \rho A\frac{\partial^2 y}{\partial t^2}u - fu \right) = 0 \quad (8)$$

Secondly, carrying out the integration by parts twice on equation (8) and taking into account the finite-element discretize model as defined by the number of finite elements in the system domain. Because a curved beam is used, there will be a coupling of axial and bending deformation.
Hence, the resultant equation is obtained as:

$$EI\int_{\Re}\frac{\partial^2 y}{\partial x^2}.\frac{\partial^2 u}{\partial x^2}dx + S\int_{\Re}\frac{\partial y}{\partial x}.\frac{\partial u}{\partial x}dx + \beta.I\int_{\Re}\frac{\partial^3 y}{\partial x^2\partial t}\frac{\partial^2 u}{\partial x^2} + C\int_{\Re}\frac{\partial y}{\partial t}u + \rho A\int_{\Re}\frac{\partial^2 y}{\partial t^2}udx - \int_{\Re} fudx = 0 \quad (9)$$

Where $\Re$ is the element domain
From the weak formulation, the equations for the finite element in terms of the stiffness, mass, damping matrices and force vector are given as:

$$\left[K^e\right] = EI\int_{\Re}\frac{\partial^2 y}{\partial x^2}.\frac{\partial^2 u}{\partial x^2}dx + S\int_{\Re}\frac{\partial y}{\partial x}.\frac{\partial u}{\partial x}dx \quad (10a)$$

$$\left[M^e\right] = \rho A\int_{\Omega}\frac{\partial^2 y}{\partial t^2}udx \quad (10b)$$

$$\left[F^e(t)\right] = \int_{\Re} fudx \quad (10c)$$

$$\left[D^e\right] = \beta.I\int_{\Re}\frac{\partial^2 y}{\partial x^2}.\frac{\partial^2 u}{\partial x^2}dx + C\int_{\Re}\frac{\partial y}{\partial t}udx \quad (10d)$$

Using equations (7), equations (10) become:

$$\left[K^e\right] = \left(EI\int_{\Re}B^T B + S\int_{\Re}A^T A\right)y \quad (11a)$$

$$\left[M^e\right] = \left(\rho A\int_{\Re}N^T N\right)\ddot{y} \quad (11b)$$

$$\left[F^e\right] = \int_{\Re} f[N]^T \quad (11c)$$

$$\left[D^e\right] = \left(\beta I\int_{\Re}B^T B + C\int_{\Re}N^T N\right)\dot{y} \quad (11d)$$

Considering the equations (11d), it can be seen that before the equation can be implemented the damping constants have to be determined first. Based on the classical work done by H.H Cudney and D.J. Inman [16], they outlined the procedures to estimate the values for each damping model and also for combination of the both models. The evaluation of the damping constants C and β was done by the least squares method also known as the pseudo-inverse routine. For the values of both C and β are evaluated by

$$\begin{bmatrix} \varsigma_1 \\ \varsigma_2 \\ \vdots \\ \varsigma_n \end{bmatrix} = \begin{bmatrix} \frac{1}{2\omega_1} & \frac{\omega_1}{2} \\ \frac{1}{2\omega_2} & \frac{\omega_2}{2} \\ \vdots & \vdots \\ \frac{1}{2\omega_n} & \frac{\omega_n}{2} \end{bmatrix} \begin{bmatrix} C \\ \beta \end{bmatrix} \quad (12)$$

The values for damping coefficients and natural frequencies can be obtained from the experimental values such those document in [14].

6. THE SYSTEM MATRIX

Conductor transverse vibration is a classic example of such practical problems in which in the differential equation both the position and time dimension have to be considered. Hence, the method use for the finite element approximation of the dynamic type element of time and space dependent equation (time dimensions).
When strung under tension, the overhead transmission lines conductors support its weight thereby sagging and sag/span ratio depends on the axial tensions at both ends. When subjected to transverse vibration, each member of the conductor is subjected to both axial and bending loads. Given that the sag/span ratio is small, the axial and transverse deformations can be decoupled. Therefore, modelling for transverse vibration for pure bending only, the axial effect can be neglected.
Fig. 3 shows the discretized model of a single span of conductor. The conductor is discretized into n number of nodes and *(n-1)* number of elements.

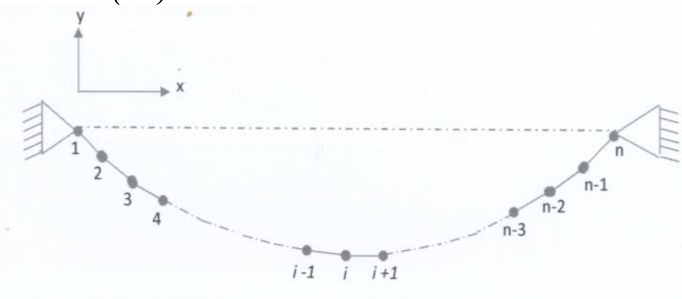

Fig 3: Discretize Model of the Conductor

The deformed beam element shown fig. 2 is mapped to form the discretize model shown fig 3. To achieve this, the reference 2D beam formulation done for the beam (fig 2) is geometrically mapped to form the global structure of conductor, where the axial deformation is neglected. The displacement of the 2D beam element expressed in the global coordinate system for the conductor and this is defined:

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$$u = \begin{bmatrix} \Delta x & \Delta y & 0 & 0 & 0 & 0 \\ -\Delta y & \Delta x & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Delta x & \Delta y & 0 \\ 0 & 0 & 0 & -\Delta y & \Delta x & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_{x1} \\ u_{y1} \\ \theta_1 \\ u_{x2} \\ u_{y2} \\ \theta_2 \end{bmatrix} \quad (13)$$

Where $\Delta x = \frac{x_2 - x_1}{L^e} = \cos\phi = c$ and $\Delta y = \frac{y_2 - y_1}{L^e} = \sin\phi = s$

Using the deformed finite element equation in eq (13) with reference to the beam element the stiffness matrix, mass matrices and load vector for the conductor are obtained as follows:

$$K_C^e = [T]^T [K_B^e][T] \quad (14a)$$

$$K_C^e = [T]^T [M_B^e][T] \quad (14b)$$

$$f_C^e = [T]^T [f_B^e] \quad (14c)$$

Where $[T]$ is transformation matrix and is defined as

$$[T] = \begin{bmatrix} c & -s & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & c & -s & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The assembly of finite element equations derived in equ (14) to form the system finite element equation requires the satisfaction of the boundary conditions as defined in the diagram of the discretize domain (figure 3). Therefore, the assembled global equation must satisfy the boundaries conditions of simply supported beam i.e.

$$u_1 = \theta_1 = u_n = \theta_n = 0$$

The above transformation results to damped equation for the transverse vibration of conductor. Thus, the system matrix equation was obtained as:

$$[M]\{\ddot{y}\} + [D]\{\dot{y}\} + [K]\{y\} = \{F\} \quad (15)$$

7. MATLAB IMPLEMENTATION

An improved MATLAB code [17] for beam element was used to simulate above finite element equation for the conductor. The code was improved to include the transformation function. The Code was written to determine the conductor static profile from which the coordinate used to determine the angle of deformation along the sag. Another code was written based on modal analysis to obtain the eigenvalue, mode shape and natural frequencies. Also, another code was developed, using the least square method to obtain the damping constant (β and C) according to equation (12).

These Matlab programs were implementation and used to simulate the numerical problem developed in the paper are for the vibrating conductor. The code was simulated to find the solution to the displacement field developed from FEA. The implementation was done for Tern conductor and physical properties are document in [14].

The simulation was used to generate the dynamic response for free vibration for three different axial tensions. The MATLAB results and the work that is documented in [14] were compared. This various results are shown table 1.

8. RESULTS

The finite element analysis modeling of transmission lines conductor simulation can be found in [14], in which the simulations of the conductor vibrations were done using ABAQUS software. In this study Matlab software was used for the conductor vibration simulation for the Aeolian vibration. Thus, finite element analysis for the mechanical oscillation for transmission line conductors was simulated using the code for deformed beam properties.

In similar manner as done for conductor vibration using ABAQUS, the eigenvalues were searched and computed in the frequency range for both conductors. For purpose of comparison results for the Tern conductor, the first ten resonance frequencies for the conductor were obtained and recorded in table 1. The comparison of the values obtained for the models were for the tensions of 20%, 25%, and 30% of its UTS.

To compute the damping constants, the modal damping from the experimental values in [14] was used. Using the experimental resonance frequencies values, the least squares method (pseudo-inverse routine) was used to compute the damping constants using Matlab. These obtained values were then used as proportional damping constants to simulate the conductor vibration for damping.

The Matlab simulation results for the eigenvalues and the natural frequencies for both conductors are presented in the tables below

Table 1: The comparison of natural frequencies values obtained from analytical, FEM and experimental result for Tern conductor

Table 1a: Natural Frequencies at 20% UTS

Natural Frequency (Hz) 20% UTS		
Analytical Model	FEM	Exp. value
4.521	4.450	5.237
9.044	8.900	10.212
13.570	13.354	14.613
18.099	17.810	19.13
22.634	22.272	22.929
27.175	26.739	29.022
31.723	31.214	32.992
37.062	35.698	37.70
40.180	40.1692	42.211
44.682	44.699	45.829

Table 1b: Natural Frequencies at 25% UTS

Natural Frequency (Hz)		25% UTS
Analytical Model	FEM	Exp. value
5.034	4.953	6.785
10.069	9.909	10.224
15.107	14.866	15.829
20.148	19.826	21.134
25.193	24.790	26.833
30.244	29.760	31.815
35.302	34.737	36.249
41.262	39.721	42.274
44.702	44.716	45.613
49.702	49.721	51.527

Table 1c: Natural Frequencies at 30% UTS

Natural Frequency (Hz)		30% UTS
Analytical Model	FEM	Exp. value
5.510	5.422	5.463
11.021	10.845	9.098
16.535	16.27	17.435
22.051	21.698	23.678
27.571	27.130	28.746
33.097	32.567	34.415
38.628	38.010	38.109
45.967	43.461	45.22
49.714	48.921	51.073
55.271	54.390	56.200

Also, the free vibration of the conductor was done to obtain its response when the conductor is subjected to some form of impact or displacement and the amplitude of vibration decay with time due to damping. A diagram of the decay is shown in fig. 4 below. The free response were done for the three axial tensions as indicated earlier and logarithm decrement was used to evaluate damping. The results obtained shows a good agreement with that documented in [14]

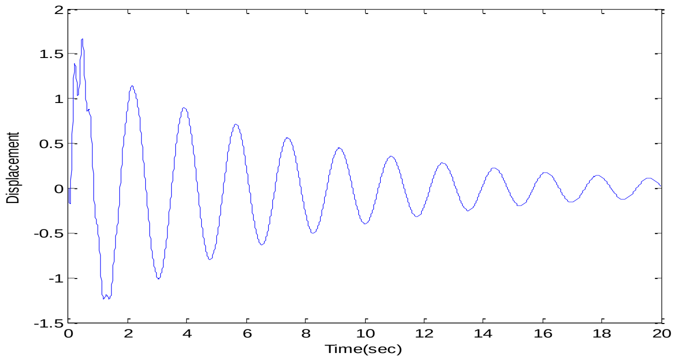

Fig 4: Free Vibration of the Conductor

9. CONCLUSIONS

The dynamic characteristic of conductors' vibration is very complex process. In this paper, a finite element model for the conductor in 2-D was developed. Finite-element analyses were used to determine the nonlinear response of the conductor system to dynamic loading from wind. The FEM implementation of a simply supported conductor model for the transverse vibration of conductor was presented for three different conductor stringing tensions.

Matlab was used to simulate the dynamic behaviour of conductor for free vibration i.e. impulse loading. The results obtained from the simulation were used to verify the effects of axial tension variations on the conductor natural frequencies. The parameters obtained from the above, to some degree of accuracy can be used to predict the response of conductors to wind loading.

This present work is being extended to implement a FEM model that includes the axial effects. This will be document in part two this work

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