CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

Each field of engineering has its specific body of knowledge, based on extensive testing and field experience, leading to empirical laws and rules for particular practical applications. However, it is clear that unifying these rules under some general mathematical and mechanical theory would allow a better understanding, and in the long run, a better prediction of the mechanical behavior of cable structures, thus reducing the need for expensive tests under varying parameters and operating conditions.

The main objective of an engineering analysis of a cable system is the prediction of cable static and dynamic behavior. Since real cable systems are usually quite complex when viewed in detail, an exact analysis of its response and energy dissipation is often not completely possible. Thus, simplifying assumptions must be made to reduce the system to an idealized version whose behavior approximates that of the real system. The process by which a physical system is simplified to obtain a mathematically tractable situation is called modeling. The resulting simplified version of the real system is called the mathematical model, or simply the model of the system.

A review of such mechanical models of cable was published by Costello (1978), with 30 references. The only general reference for overhead electrical power transmission conductors is EPRI's Transmission line reference book based on EPRI Research project 792, prepared by Gilbert (1979). This reference book presents a state-of-the-art study of conductor fatigue, aeolian vibration, conductor gallop, and wake-induced oscillation. Each chapter presents a detailed examination of the causes, mechanisms, incidence, types of motion, factors influencing motion, resulting damage, and protection methods associated with its particular topic.

Another review of cables and wire ropes of general mechanical interest was published by Utting and Jones (1984) with 77 references. This has been updated by Utting (1995), with 110 references. A review of mechanical models of helical strands was published by Cardou and Jolicoeur (1997), with 107 references. This review was restricted to elastic behavior under small deformations, which includes contact conditions with and without friction effects and possible stick slip behavior.

2.2 REVIEW OF EXISTING MODELS IN BENDING

2.2.1 Assumptions

In many of the earlier theoretical static analysis, several simplifying assumptions have been made to obtain analytical or closed form solutions. The following are the assumptions made by different authors.

1. Relative Wire Size

A strand of a large number of relatively small wires requires a different hypothesis compared with a strand of reasonable size of core and wires. The modes of contact, internal wire forces and moments and friction are closely related to the ratio of wire size. Such representation may be accommodated suitably for elastic partial-slip and gross-slip behaviours.

2. Helix angle and wire cross-section

The helix angle at any point along the centroidal axis of a wire in a strand is defined as the angle between the tangent vector to the axis and the plane normal to the axis. For cable designs with regular and lang lay in the alternate layers, the critical stresses are relatively smaller when the helix angles are close to 90^0. Hence such large helix angles are likely to promote longer life span. When helix angle is minimum, the wire cross-section is approximately ellipse. When helix angle is maximum, the wire cross-section is circular. Due consideration of this aspect is necessary.

3. End Conditions

In all practical applications, since the length of the strand is very long, studies have been carried out under “free field”, i.e., hypothesis of long length with respect to diameter. This assumption makes variations of certain quantities along the length of the wire vanish.

4. Modes of contact

Based on the wire strain, wire diameter and helix angle variation, there are three possible contact modes: lateral (wire-wire) contact, radial (layer-layer) contacts and mixed (wire-wire and layer-layer) contact (chapter 1, section1.4)

5. Material constitutive relations

The cable material is usually assumed to be linearly elastic and isotropic. The time-dependent response and linear viscoelastic behavior needs further modifications.

6. Load conditions

Normally stranded cables are subjected to axial tension, torsion and bending loads. However, the wire axial force is found to have a dominant share over the other two because the major load of the strand is along its axis and the coupling of wire bending and torsion is weak in the lay angle usually adopted for the application of overhead electrical power transmission lines.

7. Internal wire forces and moments

When a strand is loaded, each individual wire is subjected to forces and moments in the normal, bi-normal and tangential (axial) direction involving traction, shear force, twisting and bending. Strictly speaking, the major load in the normal loading conditions is in the axial directions of the strand and lay angles are small; the wire tensile force in the axial direction is the dominant load. The distribution of other loads, though small, plays a significant role in the local contact and associated slip and energy dissipation.

8. Stress and Strains

The stress and strain analysis of stranded cables were once considered too complex to be dealt with by the theory of elasticity, and therefore, various assumptions were made regarding the number and types of the loads acting on each wire in the strand in order to obtain a solution. It is assumed that the strains in the individual wires are small and that the axial and bending response are additive. In the axial case, the axial force and axial twisting moment are represented as linear combinations of the axial strain and the rotational strain.

9. Bending stiffness

The bending stiffness of the cable will be approximated by a summation of the bending stiffness of the wires in the cable i.e., treating the cable as an assemblage of helical springs. This is felt to be a reasonable assumption since friction between the wires is neglected, in the initial studies.

10. Linearity/Non-linearity

In order to simplify the complications of non-linear calculations, it is assumed that the deflection and strain are small to extend the linear theories validity.

11. Safe working loads and factor of safety

The maximum load for which a stranded cable is to be used should take into account such associated factors as friction, load caused by tension, twisting and bending, acceleration and deceleration, and, its length to the weight ratio. Factor of safety for stranded cable usually range form 3 to 4; for wire rope from 5 to 12, since there is the element of hazard to life or property.

2.3 CLASSIFICATION OF STRAND MODELS

2.3.1 Purely Tensile or Fibre Model

The purely tensile or fibre model is one the basic models adopted for the cables, when they are subjected to tension and torsion. The wires are treated as thin fibres, subjected to only pure tensile or axial forces and no moments. The simplest hypothesis for the treatment of the wire as a thin fibre was adopted by Hruska (1953) and this work paved the way for further research. Nearly a decade later, though Bert and Stein (1962) attempted to account for the curvature effects of the wire and the clenching force caused in the radial direction, it was confined to the treatment of the fibre model only. The interfacial friction was not considered.

2.3.2 Orthotropic Sheet or Semi Continuous Models

The Orthotropic sheet model assumes that the collective assembly of the helical wires in a layer is treated as a thin cylindrical annular sheet and the whole cable as an assembly of concentric thin cylinders. This assumption becomes more relevant in the cables where the number of wires in a layer is large enough to consider them as an annular cylinder. In this model the individual effects or the behavior of the wires cannot be fully handled, particularly when the wires in a layer are not having continuous contact. Hence the models that consider the cable as an assembly of thin wires, find more prominence among researchers, for the simple reason, that the individual wire behaviours can be fully represented and from that the collective behaviour of the cable assembly can be predicted. Study of this has been confined to only two teams: Hobbs and Raoof (1982) initiated the sheet model and Raoof and Huang (1992) continued it; and Cardou initiated the tube model and Blouin and Cardou (1989) and others continued it. Jolicoeur and Cardou (1991) and Raoof and Kraincanic (1994) have compared these models under axisymmetric loading.

2.3.3 Curved Rod Model

This model considers the equilibrium of the individual wires in the stranded assembly under the influence of externally applied loadings. Each wire is treated as a curved rod and the effects of wire axial stretch, bending and twisting are considered together and the cable is represented as an assembly of helical wires. The equations of Love (1944) were maintained as the basis for this model and further improved depending on the condition of friction, slip initiation etc., at the interfacial contact locations among the helical wires.

2.4 HYPOTHESIS BASED ON STRAND BENDING

Carstarphen (1931) considered an independent helical wire. A constant curvature was imposed to the axis of the cylinder on which the undeformed wire is wound. Helix angle variation was neglected. Treatment was similar to Timoshenko (1956) for the calculation of a bent helical spring, and the formula for the curvature of an independent wire was the same. Using this value, Carstarphen obtained the bending stress in a wire.

Love (1944) has presented equilibrium equations for the solution to the problem of a helical spring subjected to an axial force and twisting moment. In this approach, the spring was treated as a thin curved rod that satisfied the six nonlinear equations of equilibrium.

Lutchansky (1969) developed a simple rational mathematical model for the study of shear interaction effects in a single lay helically wound armored cable bent to a prescribed curvature. He derived expressions only for the wire axial force for a monolithic beam-like cored strand.

Costello (1977) studied pure bending of helical spring ignoring wire axial deformation. Timoshenko also analyzed it as a tip-loaded cantilever.

Huang (1977) considered wire couples, wire axial and shear forces, and studied the bending of a (coreless) two-filament twisted yarn.

Costello and Butson (1982), using a more accurate solution for helical spring bending, proposed a model in which the wires were considered as independent curved rods with no contact restraints and treated the cable as an assemblage of free helical springs. It was assumed that the strains in the individual wires were small and that the axial and bending responses were additive.

Knapp (1983) proposed a model, based on the same kinematical approach as Lutchansky (1969), but considered infinite friction (no-slip) and zero friction conditions of the wires during bending. Bending and twisting strains were calculated directly from the variation of curvature and twist between the deformed and un-deformed helices.

Lanteigne (1985) proposed a model in which the bending moment contribution came mostly from the fiber effect and calculated using the Bernoulli-Euler hypothesis and also from independent wire bending. Wire twisting was neglected and the bending moment was taken parallel to the strand neutral axis. Knapp (1988) also derived wire binormal curvature and twist for the same case but confined the study to only the wire axial strain.

Vinogradov and Atatekin (1986) studied the partial slip due to bending under a completely different set of hypothesis. A strand of finite length was assumed to be clamped at one end and loaded by a transverse force at the free end. The resulting twisting moment on each wire section was considered as periodic and inducing wire strain, which was used to evaluate energy dissipation.

Knapp (1988) calculated the bending and twisting strains assuming kinematic models for the deformed and undeformed wire, considering the extreme conditions of no-slip and zero friction.

LeClair and Costello (1988) considered the wire bending and twisting together with the wire forces but the final solution, in their own words, was ‘‘difficult to accept’’ due to very low wire axial force.

Papailiou (1997) first studied the variation of tensile force along a given wire under pointwise contact conditions. Then, he showed that the same variation may be obtained with sufficient accuracy by taking a line contact. However, his model was the simple stick/slip Coulomb model, and tangential elasticity was not considered.

Sathikh et al (2000) developed a new discrete pre-slip bending response of a strand of a helical wires having wire to core contacts under the constant curvature bending. Contacts were assumed between the core and the layer wires only (resting lay) with unlimited Coulomb friction. The core is assumed to be radially rigid. The Poissons effects on wires and core were not considered. Stretch, shear, bending and twisting of a wire in a bent strand were considered together. The effect of the wire deformation on the wire curvatures and wire twist due to the strand bending as discussed by Ramsey (1988) and Wempner (1973) was considered.

Kee – Jeung Hong (2005) published a paper on free bending on multilayered cable which was an extended version of the earlier model of Papailiou (1977). This work is however not considered here, as in their basic assumption itself, the torsional stiffness was considered to be negligible at the wire level.

Kenta Inagaki (2005) performed a theoretical and experimental study of mechanical properties of electrical cables with multilayer helical structure. When the cable is exposed to small bending curvature, the slippage of the component was prevented by the frictional force. At this stage, the components of the cable behave as solid beams. Slippage occurs between the components when the tensile force in the components overcomes the frictional force. This state occurs at sufficiently large bending curvatures and results in a variable bending stiffness varying with the magnitude of the applied bending curvature.

Rawlins (2005), with the same curved rod equations. However, his analysis is based on the “circumferential” contact mode hypothesis, where outer wires are in contact, but not with the core wire. The problem being considered is that of free bending near a clamped end, a situation similar to the case of a conductor at a suspension clamp. While Rawlins’ model is also a no-slip model, he takes into account the tangential elasticity between contacting wires. Reported results do not consider bending stiffness but, rather, strand displacements. While single-layer strand modeling presents a definite practical interest (Labrosse 1998), and also for testing the various assumptions, extension of these models to more general multilayer strands seems a challenging task.

Cardou (2006) presented a review of various mechanical models for circular section wire strands which can be found in the literature. As each model has to be based on a set of simplifying assumptions, a classification is proposed. Being a complement as well as an update to a previous paper (Cardou and Jolicoeur, 1997), several relevant references already discussed in that paper, have not been included in Cardou's review.

Goudreau (2006) conducted experimental flexure tests on an epoxy oversized one core wire and six helical wires strand; the objectives of these tests were to measure the bending stiffness and the associated strains. Three sets of boundary conditions were applied. The bending stiffness was deduced from the transverse mid span deflection and was found to be dependent on the axial force and the moment distribution. The deduced bending stiffness was compared with the values computed from the theoretical bending stiffness.

Cutler and Knapp (2010) conducted the research experiment to develop the new methodology for testing cables in bending over a sheave. A UTM machine was used for wire tension tests. An extensor meter was used to determine the stress-strain curve for the core wire of the cable specimen. The arrangement of the sheave effect was at the mid of the length of the cable specimen. The cable specimens were initially pre loaded and the wire axial strain measured at the top of the cable for varying radius of curvatures.

In addition, several models are also available for the analysis of synthetic cables. Leech et al (1993), presented a quasi-static analysis of fiber ropes and included it in commercial software: Fiber Rope Modeller. Very recently, Ghoreishi et al (2007a, 2007b,) have developed two closed-form analytical models, which can be used in sequence to analyse the synthetic cables.

With the development of Finite Element methods during the last few decades, certain authors have used the FE approach to analyze the mechanical behavior of cables. Carlson (1973) modeled the wires by bar elements as well as the connections between the wires. Jiang et al (1999, 2000) investigated the stress distribution within the wires, in a simple straight strand as well as in a three-layered straight strand, using a concise 3D FE model with prescribed displacement field.

Ghoreishi et al (2007c) developed a 3D FE model with infinite friction between the wires and the core. They also estimated the non dimensional components of stiffness matrix for a single layer metallic strand configuration various helix angles. The emphasis was placed on the linear elastic global behavior of a simple isotropic straight steel strand under small strain.

In most of the literature published to date, mostly analytical models with closed form solutions have been used, which can be applied to relatively simple cases only. The present work ventures to develop an improved model with increased accuracy. The work limits its scope only to the prediction of the response of the strand subjected to bending loads (free and constrained bending) for both single layered cable and multilayered cable. Very few researchers appear to have made studies in this direction. The finite element model of a twisted cable and analysis of the assembly (treating wires as individual entities), itself is a worthwhile work to take care of these complexities. This thesis attempts to validate the mathematical model with the results of the finite element analysis where ever applicable.

2.5 RESEARCH GAP IN EXISTING LITERATURE

The following gaps existing in available literature were identified to the best of the author's knowledge:

No multilayered strand model so far has considered together the following aspects in the formulation of the stiffness matrix of such an assembly: (a) all the six modes of strain due to three forces and three couples of the helical wire in the normal, bi-normal and axial directions; (b) more appropriate equations for the wire shear forces; (c) the wire normal force as a contributor to the strand bending moment.

The need for developing a general thin rod model, as summarized below, has therefore motivated the present analysis:

- Incorporating all aspects mentioned above and obtaining an acceptable solution for the free bending (unconstrained) response of both single and multi layered strand. In both cases, it is assumed that the wires in a layer do not contact each other while the core has frictional contact with wires of the first layer.
- Although constrained bending scenario reflects in many practical applications, the available theoretical models do not address this generic loading condition. The free bending scenario is only a specific case of constrained bending where the pulley-cable interaction is not included. Therefore a theoretical model is felt necessary.
- To validate the theoretical model proposed, development of an appropriate finite element model is required in the absence of experimental results.

2.6 RESEARCH METHODOLOGY

The methodology of the present research covers the following:

Single layered cable under free bending

- Formulation of a mathematical model to represent a single layered cable assembly to predict the strand axial force, the respective moments of the strand, the effective rigidity, and the contact stresses under free bending condition.

- Development of a finite element model for free bending analysis of a single layered cable assembly and validation of the mathematical model.

Multilayered cable under free bending

- Formulation of a mathematical model to represent a multilayered cable assembly to predict the strand axial force, strand twisting moment and strand bending moment under free bending condition. The model is further applied to situations (unsymmetrical conditions) where a given number of initial constituent wires have been cut off leading to load re-distribution in the adjacent wires. The strand axial forces, twisting moment and strand bending moments for symmetrical and unsymmetrical conditions were predicted.

- Development of finite element models for free bending analysis of a multilayered cable assembly for symmetrical and unsymmetrical conditions and validation of the mathematical model.

Single layered cable under constrained bending

- Formulation of a mathematical model to represent a single layered cable assembly to predict the strand axial force and the respective moments of the strand, under constrained bending condition.

- Development of a finite element model for constrained bending analysis of a single layered cable assembly and validation of the mathematical model.

Multilayered cable under constrained bending

- Formulation of a mathematical model to represent a multilayered cable assembly to predict the strand axial force and respective moments under constrained bending condition. Also, the wire axial strain of the top most wire of the outer layer is determined to validate the model with the experimental work available in the literature.