INVESTIGATIONS OF THE GALLOPING AND AEOLIAN VIBRATIONS OF OVERHEAD CONDUCTORS

A Thesis

submitted in partial fulfilment of the requirements for
the award of the degree of

MASTER OF ENGINEERING
IN
POWER SYSTEM ENGINEERING

By

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SEPTEMBER, 1965

CERTIFICATE

Certified that the dissertation entitled INVESTIGATIONS ON THE GALLOPING AND AEOLIAN VIBRATIONS OF OVERHEAD CONDUCTORS which is being submitted by Sri VIJAY KUMAR DESAI in partial fulfilment for the award of the Degree of Master of Engineering in POWER SYSTEM ENGINEERING of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of 12 months month from 1st August 1964 to 31st July 1965 for preparing dissertation for Master of Engineering Degree at the University.

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Dated 1.9.65

ACKNOWLEDGEMENTS

The author wishes to express his deep sense of of gratitude to Dr. T. S. M. Rao, formerly Associate Professor in Electrical Engineering in the University of Roorkee and now Professor and Head of the Electrical Engineering Department in Malaviya Regional Engineering College, Jaipur, for his valuable guidance and encouragement during the course of this work. He is also indebted to Prof. C. S. Ghosh for the facilities provided and for the permission to procure literature on the subject with the departmental funds.

(VIJAY KUMAR DESAI)

CONTENTS

SYNOPSIS

In the following pages an effort has been made to present a comprehensive picture of the various aspects of the vibration problem of overhead transmission line. The development of the subject through the last three decades has been traced and a critical analysis of the literature dealing with the theory of the problem has been attempted. The various kinds of experimental studies are described and their relative importance weighed. A reference has been made to the role of electronics in instrumentation and automatic control of vibration tests. The graphical and mathematical relationships which facilitate computation are sought to be given in a concise manner. An attempt has also been made to describe and study the old and new schemes of combating vibrations and the latest methods of their analysis based on electromechanical analogies are given. The scope of the problem is indicated and the stalemates in complete alleviation of the harmful effects are discussed. A brief reference has also been made to the importance of this problem vis-a-vis Indian conditions.

NOTATIONS

a = Area of cross section; sq. in.

b = Chord length of the cross section; foot.

d = Dia. of conductor; foot.

d_s = Dia. of conductor strand; foot.

f = Frequency; cycles per second.

f = Coefficient of viscous friction - translational.

f' = Coefficient of viscous friction - rotational.

g = Acceleration due to gravity; ft. per sec^2.

h = Length of the stub end; foot.

l = Loop length or distance between consecutive nodes; foot.

m = Mass per foot of the wire; lb.

n = Number of loops.

t = Time; seconds.

v = Velocity of the conductor; ft. per sec.

Velocity of propagation of the transverse wave; ft. per sec.

w = Weight per foot of the wire; lb.

x = Horizontal displacement; foot.

y = Vertical displacement; foot.

z = Distance along the length of the span; foot.

A = Area of cross section; sq. ft.

C = Capacitance per unit length of a line with distributed constants - farads per ft.

C_D = Aerodynamic drag coefficient.

C_{D_0} = Aerodynamic drag coefficient for that component of drag which is independent of the angle of attack.

C_K = Kármán force coefficient = dimensionless.

C_L = Aerodynamic lift coefficient = dimensionless.

C_x, C_x', C_x'' = x coordinates of the centroid, centre of viscous friction and the aerodynamic centre from the origin (shear centre). ; ft.

C_y, C_y', C_y'' = y coordinates of the centroid, centre of viscous friction and the aerodynamic centre from the origin (shear centre) = ft.

D = Drag force; lb.

D = Damping constant.

E = Modulus of elasticity; lb. per sq. in.

F = Force; lb.

F_K = Kármán force; lb.

G = Modulus of shear of stretched string; lb. per ft^2.

G = Conductance per unit length of a line with distributed constants; mho per ft.

H = Horizontal component of cable tension; lb.

I = Moment of inertia of the cross section; $inch^4$.

I_p = Area polar moment of inertia of the cross section; ft^4.

K_S = Strouhal number; dimensionless.

L = Span length; ft.

L = Lift force; lb.

L = Inductance per unit length of a line with distributed constants; Henrys per ft.

M = Bending moment; lb. ft.

P = Power transferred to termination; watts.

P = Load; lbs.

R = Reynolds number; dimensionless.

R = Resistance per unit length of a line with distributed parameters; ohms per ft.

R_m = Characteristic mechanical resistance = lb. sec. per ft.

R_0 = Characteristic resistance; ohm.

T = Cable tension; lb.

V = Relative velocity of wind stream; ft. per sec.

V = Shear; lb.

Z_a = Lumped impedance; ohms.

Z_m = Characteristic mechanical impedance; ohms.

Z_0 = Characteristic impedance; ohms.

Z_s = Impedance of the stub end; ohms.

α = Angle of the relative wind with the horizontal; degrees.

α = Real part of the propagation constant.

β = Imaginary part of the propagation constant.

θ = Angle of rotation of conductor cross section, measured about the shear center; degrees.

θ = Ratio of the effective resistance of termination to the characteristic resistance of the line.

γ = Propagation constant.

δ = Logarithmic decrement.

λ = Wavelength; foot.

λ, k = Coefficients.

ρ = Density of the medium; lb. per ft^3.

ς = Mass per unit length.

ϵ = Axial strain.

σ = Stress; lb. per in^2.

ξ - Degree of fixity; a design parameter.

η - Amplitude; ft.

ω - Angular frequency; radians per sec.

χ - Ratio of the effective reactance of the termination to the characteristic reactance of the line.

CHAPTER - 1

HISTORICAL DEVELOPMENT

1.1 Introduction

The problem of wind induced mechanical vibrations of overhead transmission lines has been of quite an amount of concern to the electric supply industry for a long time. It acquired more and more importance with the advent of long distance power transmission. Earnest attempts to alleviate the harmful effects have been made since then and it could be said that in some cases a partial success has been achieved, but the problem at its worst under severe conditions of weather and terrain has evaded satisfactory remedial measure and the elusive quest for a unique and universal solution will still have to go on for some time before the problem in its all aspects is fully explore It is still quite uncertain as to when the complete and acceptabl solution will be available.

The importance of the problem to the supply system mainly stems from the fact that it gives rise to mechanical damages and electrical outages in the transmission lines. With the present emphasis on high reliability of power supply, even at the design stage the robustness and invulnerability of transmission systems to mechanical and electrical failures receives critical attention. The increased size and cost of transmission lines, owing to the trend towards increase in the transmission voltages, makes the need of protection against all kinds of outages and failures very pressing, the mechanical problem mainly confining itself to elimimating the fatigue in conductor strands, line hardware and supporting structures and the electrical one to preventing flash overs between adjacent phases.

1.2 General Classification

The mechanical vibrations of overhead transmission lines appear mainly in two distinct forms. One is termed as the 'singing' or aeolian vibration, which is characterised by a low amplitude-of the order of one inch peak to peak- and relatively a high frequency - lying within the range of 10-100 cycles per second. Basically this is a 'forced' kind of vibration, the term implying that the alternating force producing the vibratory motion is independent of the motion and starts before the motion originates. The other type of line vibration is more properly called as 'galloping' or dancing. It is a phenomenon entirely and fundamentally different from that of the aeolian vibration. It is a self excited motion, as different from the forced vibration, which in other words means that the periodic force which sustains the motion is created and controlled by the motion itself. It (the force) therefore disappears when the motion is stopped. However to initiate this vibratory motion some external force is necessary. Once initiated, the motion builds itself up due to what is called as the negative damping till the elastic or spring action of the conductor wire brings it to a steady state. The external force is usually the wind. However ice shedding by the conductor after a snowfall could just as well trigger this type of vibration. The amplitude of this oscillation is very high and could be anywhere upto 20 feet peak to peak. The frequency is quite low being generally between 1/6 to $1\frac{1}{2}$ cycles per second.

1.3 Nature of Failures

The aeolian vibration if of a sufficiently severe nature causes high bending stresses in the conductor strands. Since these stresses are alternating or reversible, the strands are likely to give way through sheer fatigue. The points most vulnerable to failure due to reversible bending stresses are the points of support and attachment of accessories. Thus aeolian vibration with its low amplitude can only give rise to mechanical fatigue failure. Electrical flash overs between conductors are unlikely unless of course a conductor after breaking falls on another. Usually some of the spans of transmission lines keep on continuously singing with the obvious effect of reducing the normal effective life of the conductors.

Failures due to aeolian vibration are characterised by a glassy fracture which is generally accompanied by a peculiar 'S' type of curve across the diameters of the wire.

The harmful effects of galloping are rather obvious. Besides causing flexure fatigue in the wires it is likely to give rise to electric flash overs between adjacent conductors which may result in the protective relays tripping the circuit breakers and consequently shutting down the supply. Flashovers also cause the burning of the conductors at the point of contact. Mainly therefore the damage due to galloping is of electrical nature. The frequency of reversible stresses being rather very small fatigue failures are less common. Also galloping does not appear all throughout the year as does the aeolian vibration, since it requires a certain coincidence of meteorological conditions. It is observed in cold countries in winter just about a couple of times in a season in general.

Breaks in aluminium and other wires which are caused by galloping have a coarse fracture such as is obtained when small soft wires are broken in reverse bending by hand.

1.4 Developments in the Past. Literature

We will deal with the exact mechanics of these two phenomena along with their analytical explanation and various ramifications in the next chapter. Given below is a brief account of the amount of work done on this problem.

Work on the problem of mechanical vibration actually began in all its earnestness after Relf and Ower gave the aerodynamic analysis of the aeolian vibration in a paper published by them in 1921(1). This paper confined itself entirely to the mathematical explanation and analysis. However general observation of this phenomenon can be traced back perhaps to the beginning of long distance overhead transmission of power. Broad mathematical considerations were none the less given to the vibration of cables chains, steel wire ropes etc. hung in the air when these were studied in reference to the theory of suspension bridges. But power engineers began earnestly looking out for the solution of the problem only after 1921, when the first analytical paper gave some insight into the phenomenon. After this, increasingly wide attention has been given to it and numerous interesting and informative papers have appeared and a number of original theories and approaches have been suggested.

A few years after the publication of the above paper Theodore Varney gave his own idea about the nature of the problem together with an account of the experiments conducted by him in two papers published in 1923(3) and 1928(2). Although his apparatus was rather crude his conclusions as also those of Helf and Over have been generally accepted and have stood the test of time. However it must be stated that these papers have not gone into very great details of the phenomenon but merely have touched the periphery of the problem, which is understandable because that was then only the beginning of the work. Much more detailed investigation has been done since then.

A number of countries have participated in the quest or undesstanding of this problem. U.K. and U.S.A. are probably the first to enter into the field. Later Norway, Canada and U.S.S.R. and much later France took active interest, and lately Japan has also joined into make some significant contributions. The technical literature on the subject mainly consists of papers published in the technical journals, bulletins and committee meeting reports from these countries. The problem has received a rather scant attention in text books as it is much too a specialised area to be encompassed in any general text book on vibration or transmissio line practice without doing injustice to it, considering its vastness.

The first paper on galloping of transmission lines was available only in 1932 (4) when J.P.Den Hartog gave an account of his concept of the phenomenon together with a little analytical treatment. His view was mainly limited to the simplest kind of galloping i.e. the 'tersion free' type.

Broadly the subject of mechanical vibrations of both the types has been studied under the following heads by the different investigators.

(1) Theoretical analysis and explanation of the mechanics of the phenomenon.

(2) Experimental studies on laboratory spans, outdoor test spans and actual line spans.

(3) Measurement and control of the various variables in the vibration tests.

(4) Means of suppressing the two types of vibrations.

(5) Analog methods.

Most of the papers available touch upon only one aspect of the problem which makes it possible to sort them out as such. However there are some papers which deal with more than one aspect simultaneously.

Besides Varney, Wolf and Over, contribution to the theory of the aeolian vibration problem has come from Monroe and Templin (1932)(5), Buchanan (1934)(8) and Steidel (1956)(27) to mention only a few. We will come to the critical review of their papers in a chapter specially devoted to it.

As far as galloping is concerned few people have gone into the mathematical details which happen to be much more complicated than in the first case. After Den Hartog and C. O. Harris the only papers which made substantial contributions in this area are those by McDaniel (1960)(29), Davis, Richards and Scriven (1963)(34) and Simpson (1965)(35), who have given quantitative relations arrived at analytically and otherwise. Rathouchi's paper (1963)(31) also gives a new angle to the problem. The paper by Edward and Madeyski (1956)(10) though largely dealing with experimental work gives in the course some glimpses of the analysis behind it.

The experimental study of the mechanical vibrations of power conductors has been very exhaustive and a great wealth of information exists in the form of technical papers as if to compensate for the rather inexact nature of the analysis. This is probably due to the reason that a number of studies have been sponsored by various power commissions, power supply services and the concerned utility industries in this direction, this being a major problem they have to deal with. The largest single contribution perhaps comes from the Hydro Electric Power Commission of Canada, whose staff has the largest number of papers to its credit. The American Institute of Electrical Engineers has also encouraged research in conductor vibration and the conductor vibration session of its fall general meeting in Oklahoma City in the year 1950, gave a number of papers on this subject which is a great store of knowledge for the new investigators. To mention a few other institutions which have conducted studies on this problem are: the National Research Council of Canada, State Colleges of Iowa and Washington, Universities like Purdue, Notre Dame, Bristol, Utilities like the Aluminium Corporation of America, Preformed Line Products Company etc., the National Physical Laboratory of England and others.

The papers of importance in the experimental aspect of the subject are by Stickley (1932)(6), Wright and Mini (1934)(7), Carroll (1936)(9), Tornquist and Becker (1947)(13), Lummis and Klopfenstein (1950)(15), Edward and Madeyski (1956)(16), Farquaharson and McHugh (1956)(17), Tompkins, Merril and Jones (1956)(18), Davis, Richards and Scriven (1963)(34) and Ratkowski (1963)(31). Messers Edward and Madeyski have been working on this problem for years and their contribution is very noteworthy. They have conducted long term studies of the vibration phenomenon under various atmospheric and meteorological conditions and have obtained very valuable information.

Measurement and Control of vibration tests has also been a relatively popular field and a number of individuals have taken keen interest in it, and have brought about a vast refinement and sophistication in the instrumentation. The first paper devoted entirely to measurement and control appeared in 1941 (12) by G. Tebo and was followed by various others. The papers by Moulins and Harvey (1969) (22), Kuhlman, Poffenberger and Grosshandler (1969) (20) and Schemburg and Trobby (1969) (23) have given electronics its due place in the instrumentation as also in control. These contributions are most noteworthy since they have increased the precision and facility or the measurements several-fold. The second paper gives the report of a mobile vibration laboratory unit (Dynalab) which can be taken from tower to tower and thus making the job of outdoor line span testing very much simpler. The unit has built in telemetry with various types of electric transducers indicated for metering different quantities. Electronics no doubt increases the complication of building the instrumentation systems and of handling after assembly, but that is inevitable if sensitivity and selectivity of instrumentation system is to be kept high. However attempts have been made to produce oscillographic records of the amplitude and frequency data of a reasonably accurate nature with simple electromechanical compact instruments. One such being the live line vibration recorder produced by the Ontario Hydro, an account of which appears in a paper by Edward and Boyd (1963)(32).

The literature on the means of suppressing conductor vibration is also fairly large. The first paper giving the description of the Stockbridge damper was published by Stockbridge himself in the Elec. World in 1925(45). In its original form it was a crude device. But with all the refinements which it has undergone it has become the mostly widely used damper. The earlier practice before the advent of other types of dampers was to use armour rods, festoons, preformed reinforcing at supports cable absorbers etc.

The paper by Speight (1941)(11) suggests the use of torsional damper which has also been found to be quite effective. The latest among dampers, the single degree of freedom type has been suggested by Bouche, Ensor and Tengwal in their 1963 paper(30)

Besides these papers there are others like those by Edward and Sproule (1959)(23) which have suggested novel methods of suppressing vibration.

Most of the above schemes provide protection against aeolian vibration. The galloping seems to be a lot more difficult to suppress. However partially successful schemes such as winding P.V.C. tape on the conductor to make its cross section aerodynamically stable have been suggested by Davis Richards and Scriven (1963)(34).

Analog studies of conductor vibration is a refreshingly new aspect as it eliminates the tedium of actual line testing. Electric analogies and others such as the structural beam analogy have made the work very much simpler. However a perfect analogy i.e. the one that holds true under all conditions is difficult, but reasonably accurate simulation has been possible. The papers of importance in the study of this aspect are by Tompkins, Merril and Jones (1956)(18), Steidel (1959)(27) etc.

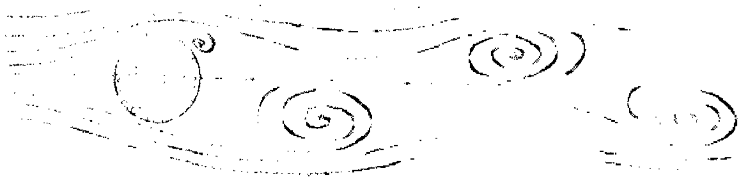
CHAPTER - 2

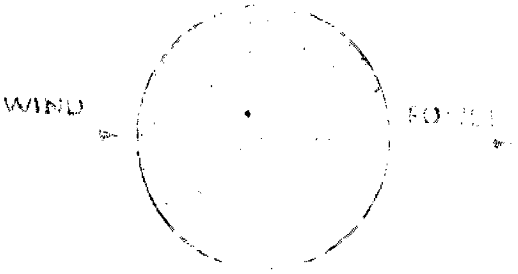
MECHANISM OF CONDUCTOR VIBRATIONS - A LITERATURE INVESTIGATION

2.1 Aeolian Vibrations

The basic physical phenomenon behind aeolian vibration is aerodynamic and can be explained in terms of the dynamic behaviour of the medium in which conductor is suspended.

When a fluid medium such as air or water flows past an obstruction in ~~the~~ its path, eddies are produced behind the obstruction (Fig. 2.1). If this obstruction is symmetrical in cross section as considered from the direction of the fluid flow (e.g. a circle) the eddies thus formed will react similarly on each face of the obstruction (the top and the bottom). As the fluid flows past the obstruction, because of the minor irregularities on the surface the friction on the two sides is not exactly the same at any particular instant. As a result of this the velocity of the fluid near one surface will tend to be higher than that near the other. According to the well known laws of fluid mechanics the pressure of the fluid moving with higher speed will be lower than its counterpart moving near the opposite face of the obstruction. This difference of pressure on the two faces of the obstruction gives rise to a force at right angle to the fluid motion but acting on the obstruction. However the non uniformity of the density of the fluid medium in the two areas causes a flow of fluid from the high density side to the low density side. This action of the fluid is in the form of eddies or swirls which in the aerodynamic parlance are called as the Karman's vortices. As the rarified area is

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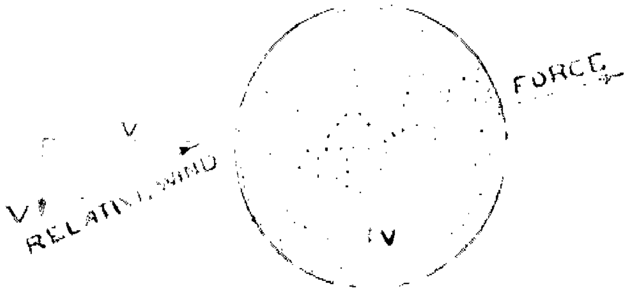
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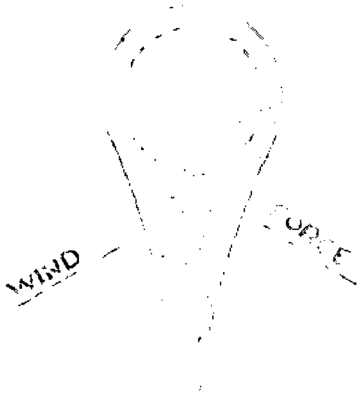
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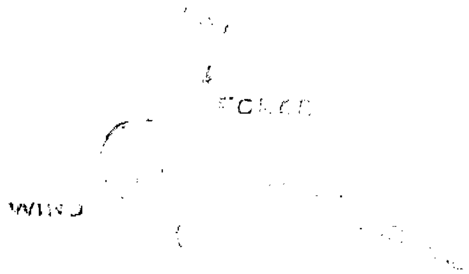
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restored to normal density by the inflow of eddies the velocity on that side is reduced and the inrush of eddies accelerates the motion on the other side. As a result of this the fluid on this side now moves with higher velocity than on the opposite surface. Clearly the situation has been reversed and at this instant the eddies cease from the previous side and begin on the other. This cycle of events is repeated again and again.

Due to the fluctuation of velocity of the fluid on the two sides, the pressure difference also acquires the pulsating property and this gives rise to a periodic force on the obstruction in a plane at right angles to the flow of the fluid. This kind of periodic force is responsible for the aeolian vibration of the overhead conductors. This alternating force is present only when Reynold's number ($R = 6380\ Vd$, where V is in ft. per second and d in ft.) falls between 100 and 200 000. Under $R = 100$ no vortex is detached and over $R = 200\ 000$ the disturbance in the wake appears to be random. When the frequency of the alternating force is near or equal to one of the natural frequenci of the conductor span resonant vibrations result.

The frequency of the periodic force can be shown to be equal to

$$f = \frac{Ks.\ V}{d} \quad \text{-----------------} \quad (2,1)$$

Where Ks is the dimensionless Strouhal number and is in the neighbourhood of 0.185 in the normal meteorological condition V is the velocity of the air stream in feet per second, d is the diameter of the conductor in feet.

For smooth circular cylinders Ks is considered to be substantially constant between $R = 1000$ and $R = 50\ 000$. However under R = 1000, Kc falls off sharply while over R = 100 000, Kc increases very rapidly. As explained earlier the eddy shedding on alternate sides of the cylinder causes a harmonically varying force on the cylinder in a direction perpendicular to that of the stream. The maximum intensity of this force can be written in the form usual for most aerodynamic forces (such as lift or drag) as follows

$$F_K = (C_K \frac{1}{2}\rho V^2 . A) \sin \omega t. \quad - - - - - - (2.2)$$

The subscript K stands for Kármán, F_K being Kármán force and C_K the dimensionless Kármán force coefficient. The value of C_K is not precisely known but roughly can be taken to be equal to unity which holds good for a large range of Reynolds numbers from 10^2 to 10^7. ρ is the density of the medium.

In a freely suspended wire, assuming the tension to be constant of a transverse wave propagation velocity is

$$v = \sqrt{T/m} = \sqrt{T.g/w} \quad - - - - - - - - - (2.3)$$

v = Velocity of wave, feet per sec.

T = Total tension in the wire - pounds.

m = Mass per foot of wire.

w = Weight per foot of the wire in pounds.

g = acceleration due to gravity, feet/sec^2.

The velocity remaining the same the product of the wave length and frequency is constant and is equal to the velocity; that is

$$2\lambda . f = v \quad - - - - - - - - - - - (2.4)$$

where λ = The distance between nodes.

f = Frequency in cycles per second.

Hence the natural frequency of the span is found from equating the equations 2.2 and 2.4.

$$2\lambda.f = \sqrt{\frac{T.g}{w}} \quad ------ (2.5)$$

or $$f = \frac{1}{2\lambda}\sqrt{\frac{T.g}{w}} \quad ------ (2.6)$$

If the line is vibrating in its fundamental mode the val of will be equal to the span length L; from which

$$f_{nf} = \frac{1}{2.L}\sqrt{\frac{T.g}{w}} \quad ------- (2.7)$$

The higher natural frequencies or harmonics will be simple multiples of f_{nf}, the fundamental natural frequency.

A relationship between the wind velocity and loop length into which a given span will tend to vibrate may be obtained by equating the frequency of the eddies of the wind (eqn. 2.1) to the natural frequency of vibration into loop length λ.

$$\frac{K_s.V}{d} = \frac{1}{2.}\sqrt{\frac{T.g}{w}} \quad ------ (2.8)$$

$$\lambda = \frac{d}{2.K_s.V}\sqrt{\frac{T.g}{w}} \quad ------ (2.9)$$

or $$\frac{L}{n} = \frac{d}{2.K_s.V}\sqrt{\frac{T.g}{w}} \quad ------ (2.10)$$

where n is the number of loops (any integer).

$$\therefore V = \frac{n.d}{2\cdot K_s\cdot L}\sqrt{\frac{T\cdot g}{w}} \quad ------ 2.11)$$

$$V_{min.} = \frac{d}{2\cdot K_s\cdot L}\cdot\sqrt{\frac{T\cdot g}{w}}$$ – the min value of V for resonance

(2.12)

Aeolian vibration from the above explanation of its mechanism of excitation can be looked upon as a 'forced' type of vibration. The alternating force producing the vibratory motion, as will be observed, is quite independent of the motion of the conductor and in fact it starts before the motion originates which is the criterion for any type of forced vibration as defined in aerodynamics.

2.2 Galloping

Galloping is a case of self excited vibration caused by the wind on a wire which has assumed a non circular cross section due to any accumulated sleet or any other reason.

When wind blows against a perfectly smooth circular cylinder (Fig. 2.2a) it exerts a force on the cylinder having the same direction as the wind. This is evident from symmetry. For a rod of non circular cross section (Fig. 2.2b) this in general does not hold true, but an angle will be included between the direction of the wind and that of the force. A well known example of this is given by an airplane wing where the force is nearly perpendicular to the direction of the wind (Fig. 2.2c).

Let us visualise the transmission line in the process of galloping and fix our attention on it during say the downward stroke. If there is no wind the wire will feel air blowing from below because of its downward motion. If there is a horizontal side wind of velocity V, the wire moving downward with velocity v, will experience a wind blowing at an angle $\tan^{-1} v/V$ slightly from below. If the wire has a circular cross section, the force exerted by that wind will have a small upward component (Fig. 2.3). Since the wire was moving downward this upward force component of the wind exerts a force in opposition to the direction of motion of the wire and thus damps it. However, for a non circular cross section it may well be that the force exerted by the wind has a downward component and thus furnishes negative damping (Fig. 2.2b).

Considering the conditions during the upward stroke of the vibration it can be seen in a similar manner that the relative wind felt by the wire comes obliquely from above, and the force caused by it on a circular wire has a downward component which causes damping. For a non circular section it may be that the force has upward component, and this component being in the direction of motion acts as a negative damping.

If the sleet accumulated on the wire gives a cross section exhibiting the relation between the wind and the force direction shown in (Fig. 2.2b) we have a case of dynamic instability. If by some chance the wire acquires a small upward velocity, the wind action pushes it even more upward, till the elastic or spring action of the wire stops the motion. Then this elastic force moves the wire downward, in which process the wind again helps, so that small vibrations soon build up into very large ones.

The aerodynamic instability of the geometrical cross section of a conductor it can thus be seen is alone responsible with the definition of a self excited vibration where in the force which sustains the motion is created and controlled by the motion itself.

It is therefore necessary that a criterion be devised by which the stability or instability of any particular cross section could be precisely predicted. This brings us into the domain of aerodynamics and of irregular cross section where little general knowledge exists. In the case of simple geometric profiles of conductors such a prediction through qualitative reasoning is possible but a general method for all irregular cases is not available and then the only means available is the experimental study. We will newconsider the qualitative reasoning for a typical case.

The most unstable cross section so far known is the semicircle with its flat face turned towards the wind. Fig.2.4 shows such a section in a wind coming slightly from above, corresponding to the upward stroke of a galloping line. The air stream leaves the cross section at the sharp edge at the bottom but can follow around at the upper sharp edge for some distance on account of the wind coming from above in a slightly inclined direction.

The region filled with dots is filled with very irregular turbulent eddies the only known property of which is that in such a region the average pressure is approximately equal to atmospheric. On the lower half of the circular surface of the cylinder thus we have atmospheric pressure that is the pressure of the air at some distance away from the disturbance created by the line. Above the section the streamlines curve downwards. This means that the pressure decreases when moving from a to b, which may be seen as follows. Consider an air particle in a streamline. If no force were acting on it the particle would move in a straight line. Since its path is curved downwards a force must be pushing it from above. This force can only be caused by a greater pressure above the particle than below it, so that pressure at b must be lower than that at a which being far away from the disturbance is atmospheric. Thus because the pressure on the lower half of the circular periphery is greater than that just immediately above it the cylinder experiences a vertical force upwards. This being so during the upward stroke of the cross section constitutes negative damping and gives rise to self excited galloping.

It is obvious that this kind of qualitative reasoning can not be applied to all cross sections and a more critical approach is required. This need is met partially by a mathematical cum graphical method which will be presently described. For this purpose it is essential to define two aerodynamic quantities called the 'Lift' and the 'Drag' on a cross section. The former is the resolved component of the total air force (wind force) in a direction perpendicular to that of the wind velocity relative to the cross section denoted by L and the latter is the resolved component in the direction of the relative wind velocity and is denoted by D.

Consider any arbitrary cross section Fig. 2.8 moving downward in its vibratory motion so that the wind appears to come from below at an angle $\alpha = \tan^{-1} v/V$. The lift and drag L and D have vertical upward components opposite to the direction of the motion of $L \cos \alpha$ and $D \sin \alpha$. The total upward damping force F of the wind

$$F = L \cos \alpha + D \sin \alpha \quad \text{----------} \quad (2.13)$$

The force F in itself is not of much significance but its rate of variation with respect to the angle of attack α is $(\frac{dF}{d\alpha})$. So long as α remains small it can be considered to be equal to v/V (radians). Therefore assuming absolute wind velocity V to be constant) indirectly we are considering rate of variation of the force with the conductor velocity.

The importance of this differential can be explained as follows. Assume $\frac{dF}{d\alpha}$ to be zero at all times. The inference is that the force is independent of the motion of the conductor and is constant at its value. Any vibration or galloping would not change it and it naturally would not have any effect on the vibration (so long as it is not alternating). On the other hand assume $\frac{dF}{d\alpha}$ is negative which would mean that the upward wind force increases for decreasing value of α. Reckoning α positive in the counter clockwise direction, and the force positive in the upward direction, this would mean that as the conductor has a decreasing downward velocity or increasing upward velocity the force F in upward direction increases. This clearly is encouraging condition for negative damping and producing galloping.

Therefore the criterion for dynamic instability is that $\frac{dF}{d\alpha}$ be less than zero.

$$\frac{dF}{d\alpha} < 0 \quad \text{-----} \quad \text{unstable} \quad \text{-----} \quad (2.14)$$

For $\frac{dF}{d\alpha}$ equal to or greater than zero the dynamic conditions are stable

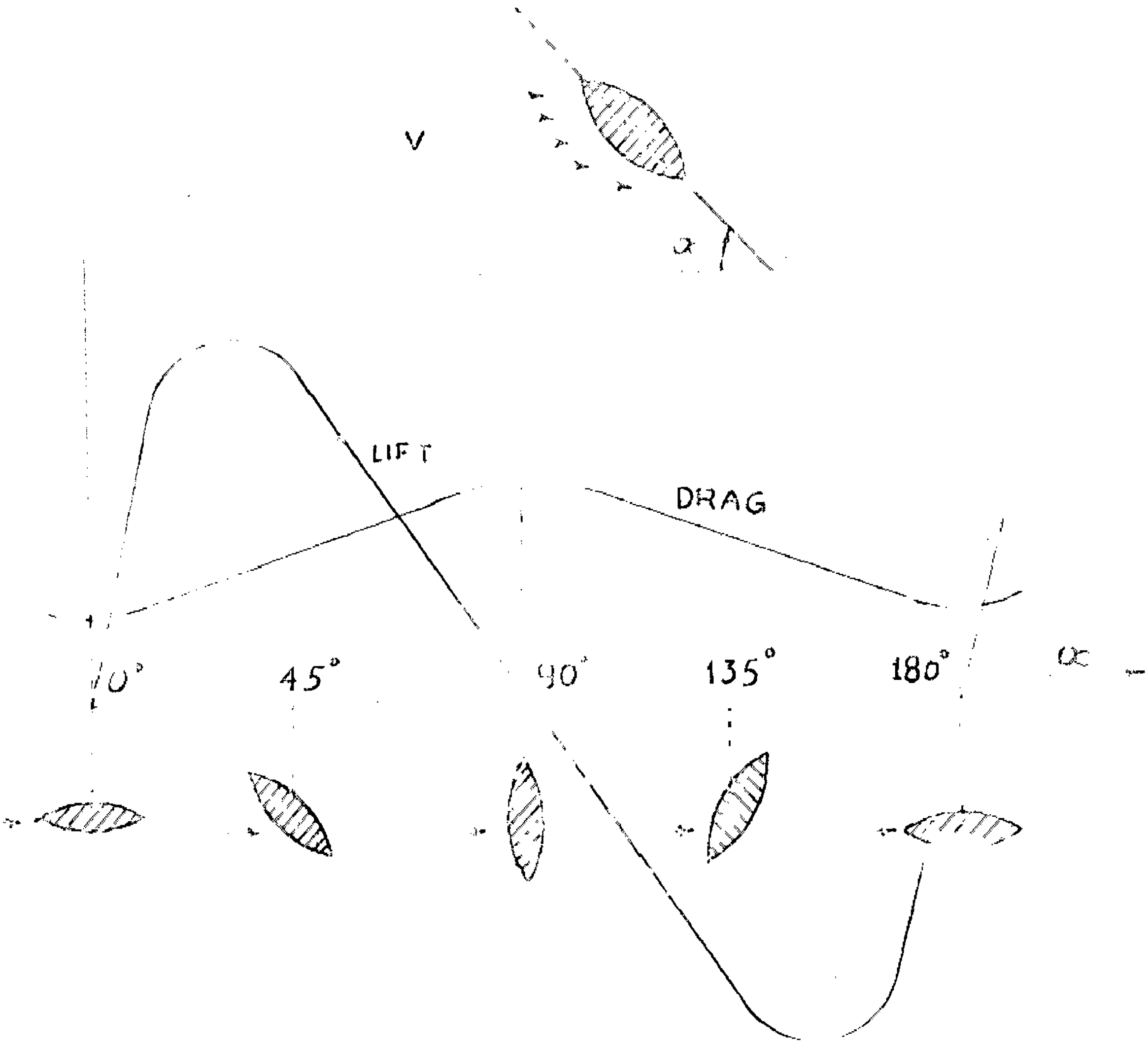
$$\frac{dF}{d\alpha} = \frac{d}{d\alpha}\left(L \cos\alpha + D \sin\alpha \right) \quad \text{----} \quad (2.15)$$

$$= \frac{dL}{d\alpha}\cos\alpha - L\sin\alpha + \frac{dD}{d\alpha}\sin\alpha + D\cos\alpha$$

$$= \sin\alpha\left(-L + \frac{dD}{d\alpha}\right) + \cos\alpha\left(\frac{dL}{d\alpha} + D\right)$$

For small α, $\cos\alpha$ is unity and $\sin\alpha$ is negligible as compared to unit.

$$\therefore \frac{dF}{d\alpha} \quad \frac{dL}{d\alpha} + D \quad \text{.........} \quad (2.16)$$


V
α
LIFT
DRAG
0°
45°
90°
135°
180°
α

Therefore the condition for dynamic instability is that

$$\frac{dL}{d\alpha} + D \quad < \quad 0) \quad - - - - - - - - - - (2.17)$$

The values of lift and drag of an arbitrary cross section can not be calculated from theory very precisely but can be found from wind tunnel tests (Chapter 5). The results of such tests are usually plotted as Lift vs. angle of attack and drag vs. angle of attack curves Fig. 2.6.

The given cross section having these whose Lift and Drag curves is unstable if :

<u>The negative slope of the lift curve is greater than the ordinate of the drag curve for any angle of attack on these curves</u>.

A cross section can therefore be stable for a certain range of α and unstable over the rest of the range depending upon the nature of L vs α and D vs α curves.

From Fig. 2.6 it can be observed that elongated section is stable when held along the wind ($\alpha=0$) and unstable when held 'across' the wind ($\alpha=90^{o}$). A transmission line conductor after ice and sleet format'on has an cross section more or less elongated in vertical direction - a condition obiviously conductive to galloping.

contd.

2.3 Further Modifications of Galloping

The problem of galloping or dancing of conductors is additionally complicated by the introduction of torsional motion in the conductor[**] As a generalization three types of galloping could be considered. The first is the torsion free galloping which does not require torsional motion either to start or to maintain vibration. Second there is elliptical torsionally modified galloping, which too does not require torsional motion to start or maintain it but which due to its eccentric cross section develops a torsional motion which modifies the motion of the conductor. Third there is elliptical torsionally controlled galloping which requires torsional motion to start and maintain it. A comparison of the three types of galloping is given below.

The torsion free galloping occurs, usually after light ice deposits during low or moderate wind velocities, the motion being in vertical plane with little or no torsion. The frequency of galloping is the natural frequency of the line. This kind of motion is generally initiated by a travelling wave which also controls the mode of the vibration. In spans with dead end this type of galloping is unusual.

[**] According to certain theories, torsional motion is an integral part of the galloping phenomenon and its coupling with the translational motion is responsible in most cases for large amplitude of vibration.

The 'torsionally modified galloping' displays an elliptical motion under moderate or low wind velocities. The frequency is again one of the natural frequencies of the line. The torsional motion occurs at the same frequency and is usually either in phase or 180° out of phase with vertical motion. Galloping of this type in the first mode is unusual in spans with dead ends.

The torsionally controlled galloping occurs at high wind velocities after heavy ice deposits on the line. It also traces an elliptical path but the frequency is not always at a naturall frequency of the line. The first mode galloping is found even in spans with dead ends. This kind of motion is not initiated by any travelling wave but by torsion.

2.4 Other Types of Vibrations

Vibrations of large amplitude and low frequency caused by mere swaying of the condutters by wind are found to occur in all transmission lines when the conductors are stretched very tight. This is called as whipping and has harmful effects.

Vibrations due to corona effect appear only when the line is energised. These are not very serious.

CHAPTER - 3

CRITICAL REVIEW OF THE ANALYTICAL TREATMENT OF AEOLIAN VIBRATION AND GALLOPING

3.1 General

This chapter will deal with the review and criticism of the analysis done so far in the line vibration investigations. It is not however intended, to give actual mathematical formulae derived in the various papers, here. These will be found in chapter 7.

The analysis of aeolian vibration problem for reasons to an extent already discussed, mainly consists of evaluation of the frequencies as functions of the line parameters, the stresses and strains at the supporting structures. Being a forced kind of vibration, the presence of an external force is absolutely essential for its sustainance. The frequency of this external force i.e. the strouhal eddy frequency is independent of the natural frequency of the line, and depends on the wind velocity and the conductor diameter only. The resonance occurs when this frequency coincides with one of the natural frequencies of the line. The energy derived for the motion is entirely from the wind as there is no such thing as a negative damping present. The effects of aeolian vibration on the conductor are entirely confined to the stresses at the supports and at the nodes of motion.

The galloping being a self excited motion the presence of an external force is not strictly necessary. The motion is excited, controlled and mostly energised by its own self and therefore the power input from the wind is not a very important factor and thus has inspired less detailed studies as far as galloping is concerned. The frequency of oscillations in this case can be any of the lower natural frequencies of the line in which the conductor by accident happens to start vibrating. The negative damping, which is a characteristic of the conductor cross section, will help maintain whatever kind of motion the conductor acquires due to the initial disturbance. The stresses and strains problem is entirely similar to the aeolian vibration problem, except perhaps that the loop length for the latter being much smaller (or the number of loops greater) as compared to the former, the bending is more and correspondingly the stresses are large. As explained earlier, mechanical damage to the conductors is rather less frequent in galloping but the electrical flash overs are comparitively very much more serious owing to the large amplitudes of oscillations.

Because of the above reasons the analytical investigations in aeolian vibration phenomenon are largely confined to the stresses and strains studies and in galloping to developing criterion for aerodynamic instability of the conductor profile.

The damping methods, the analysis of dampers and the criterion for their efficient and optimum use form an important part of the analysis, but these are studied separately from the general vibration analysis.

3.8 Review and Criticism

Though all the above aspects of analysis have been given in bits in a number of papers in the last 30 to 36 years, a comprehensive treatment combining all of them is not available in any single paper. The earlier investigations were in fact based on very little mathematical analysis-whatever that was made available by Relf, Cuer, Varney and Den Hartog (1, 2, 3, 4). The work of the first three authors was mainly in the region of determination of ranges in which the Strouhal eddy frequencies and the line natural frequencies can coincide, which viewed from the present stage of development in the analysis, was very elementary and even insignificant. Their more important contribution was to the theory of the problem, in the sense that they were the first to look deeper into the phenomenon and explain the basic mechanism thereof. Similar work in the field of galloping was done by Den Hartog. He not only gave the explanation of the mechanics of galloping but gave, though not a fully rigorous and mathematical, a graphical cum mathematical analysis regarding the profile stability. What is important is that these theories have stood the test of time since they were propounded in the early twenties and thirties respectively, and have not been disproved till today. In absence of any other theories of equal rationality, these have by a large, been accepted as they are all the subsequent investigators.

3.8.1 Aeolian Vibration Analysis

The only papers of importance in the analysis of aeolian vibrations are those by Farquharson and McHugh(17) and

Steidel(27). The first one, which is a joint paper in fact with ref. 18, gives the relations for the energy imparted to a span by wind. Experimentally this has been verified very exhaustively for various types of conductors (roughness varying from smooth circular to 6/1 A. C. S. R. conductors) and a kind of generalization has been achieved. The authors have proved experimentally that the pattern of stranding or the conductor roughness has very little effect on the power curve in the low amplitude region. The general relation obtained by curve fitting for all types of conductors shows that the energy imparted to each foot length of the span is a polynomial (as ascending series) in the amplitude of oscillation. The actual expression will be found in chapter 7 which deals with all the quantitative relations. Prior to this paper rather scant information was available on the wind excitation in quantitative terms and therefore this paper must be termed as a major break through for further investigations. The conclusion about the independence of wind energy and the degree of roughness of the conductor itself is very important. Mathematically this has not been proved and perhaps may never be proved because the approximation is true only in the low amplitude ranges (as are normally encountered in aeolian vibrations) and in the higher ranges the departure is quite appreciable.

The stresses and strains in conductor at the points of flexure has also received critical attention. Initially it was thought that the structural beam analogy would be eminently useful and the bending stresses could be easily worked out. The problem however turned out to be much more complicated than this, because of the presence of dynamic bending moments and shear forces due to vibration and their superimposition on the static bending moments and shear forces because of the conductor sag. Additional complication was the absence of total flexibility or total rigidity in the clamps at supports. Most of the clamps that have been in use for the last two decades or more have the required flexibility introduced in them through careful design. Analytically this is very difficult to take into account. The paper by Stickley (6), solved the case of the conductor vibration almost completely for static and dynamic stresses with the assumption of absolute rigidity of supports. This was for reasons already mentioned, an incomplete solution and had limited applications. Its importance at that time was much because of the fact even this kind of solution was not obtained previous to this and also because the estimates of stresses and strains which it made were on the conservative side.

Further exploration of this aspect remained neglected for a long time after the publication of Stickley's work and it was only in 1959 that a rigorous solution of stresses at flexible supports was available in the paper by Steidel(27). In fact this paper deals with all kinds of supports, namely, the totally rigid (on the lines of Stickley), totally flexible (like a beam supported on hinges) and the most important that is partially flexible supports. The solution involves differential equations that are used in all the usual bending calculations. Under rigid clamping or the opposite that is in the hinged or pinned supports the approach involves mere substitution of the necessary boundary conditions (the deflection, slope or bending moment as the case may be) in the general solution of these very things. For partially rigid clamps the the boundary conditions are rather elusive. The paper by Steidel is remarkable in the sense that with an original approach this difficulty has been overcome. The method consists of introduction of a parameter ξ which represents the fraction of the actual conditions that can be represented by the pinned end conditions. The fraction $1 - \xi$ represents that portion of the maximum bending moment for the fixed ends (or rigid ends), which actually exists at the clamp. This factor $(1-\xi)$ is called as the degree of fixity.

The actual approach of the analysis is as under.

First the static conditions are considered, that is, with no vibration present. The equations for the deflection, slope, bending moment and shear force at any point on the conductor with general end conditions (clamped, pinned etc.) are derived and stresses and strains worked out for the composite conductor as well as the outer most. Strands, according to the elementary principles of strength of materials. Then, the motion of an element of the conductor is considered and according to the Newton's second law, the dynamic forces acting on the conductor due to shear, tension and displacement are equated to its product of mass and acceleration. Using the general equations for deflection, shear etc. under static conditions as derived earlier, the final equation of motion of motion (a partial differential equation of fourth order) is obtained. This equation for its solution will give the vertical displacement as a function of time and space (i.e. the distance from the origin). The solution is found by assuming it to be a product of two functions each a polynomial in one variable only (time or space). The time dependent solution is readily found by classical methods. The space dependent solution is then found similarly, but the arbitrary coefficients of the solution polynomial will depend on the actual boundary conditions. If one loop of the vibration near one support is considered (the span vibrating in a number of loops), then the boundary conditions will correspond to pinned - partially pinned ends be cause the loop considered has the support clamp at one end and a node at the other. This node behaves like a pinned end i.e. the displacement at it is zero and there is no rigidity, therefore the bending moment is also zero. For the partially pinned support the bending moment is equal to $(1 - \xi)$ times the maximum bending moment for a fixed end by definition, the displacement again being zero. With this substitution it is possible to evaluate the arbitrary coefficients and thus find the time independent solution. The complete solution is the product of the time independent and the time dependent solution.

Knowing the maximum bending moment at an actual suspension clamp, the loop length of the first loop from the clamp and flexural rigidity of the cable, would make it possible to evaluate , indicating how well a given clamp design reduces or alleviates the stresses due to wind induced vibrations. (It therefore should be a useful parameter in the improvement of clamp design , the optimum design being that which shows the highest value of   over the frequency range where the most damage to cable is sustained.

After the evaluation of bending moments and displacement the stresses and strains can be worked out in a manner identical to that for the static cases.

The analysis of dampers used for combating aeolian vibration is found in quite a few number of papers. The paper by Strum(10) deals with the Stockbridge damper analysis quite elaborately, in a conventional way. The torsional damper is analysed partly mathematically and partly experimentally in the paper by Speight(11), again in a vonventional manner. The single degree of freedom damper(30) has not been subjected to mathematical treatment of this sort as yet, as it is comparatively new. However the analysis of dampers is approached in an entirely different way by Tompkins, Merril and Jones(18) i.e. on the basis of electromechanical analogies with special reference to the mechanical impedance of the dampers. These are discussed in detail in chapter 8. This method has now become the standard method of damper analysis and prediction of damper performance and the conventional methods are rarely resorted to.

3.2.3 Galloping Analysis

Relatively fewer number of papers dealing with analysis of galloping are available. Den Hartog's graphical cum mathematical analysis is no doubt useful but is not completely satisfactory as it is based on a number of assumptions. It does not consider for instance any forces on the conductor except the lift and drag, while there are many other which are quite important though hot as important, such as inertia forces, the visions friction forces etc. After Den Hartog, upto 1960 hardly any paper has been written which analyses galloping mathematically. McDaniel's paper (29) is an important break from this stalemate. The aspect explored is again the aerodynamic instability of arbitrary cross sections, but, this has been done in a far more rigorous and precise way and no resort has been made to graphical or experimental methods.

McDaniel's paper analyses galloping in the following manner.

First the various forces acting on the conductor are considered. There include :

1) Inertia forces-produced by the conductor displacements - acting through the centroid of the cross section.
2) Weight of the conductor acting through the centre of gravity.
3) Viscous friction forces - produced by the displacement - acting through the centre of viscous friction.
4) Horizontal and vertical components of the tension - acting through the shear centre.
5) The aerodynamic forces, namely, the lift and drag forces acting through the aerodynamic centre.

The sum of the resolved components of these in the vertical and horizontal directions equated to zero give us two partial differential equations second order.

The motion of the conductor in actual vibrations is not only translational but there is also a torsional or rotational motion present. To take this into account, various torques acting on the conductor are considered. These consist of, in addition to the torques contributed by all the above forces (except the IV which passes through the shear centre) about the shear centre, the following :

1) Inertia torque - due to rotational displacement
2) Rotational viscous friction torque

The rotational aerodynamic torque is also there but at low wind velocities it is so small that it can be neglected.

Cut summation of all the torques listed above and equating them to zero another partial differential equation in time and space (distance from the origin of the point considered on the length of the conductor), is obtained.

The three partial differential equations (each of second order) that are thus obtained describe the motion completely.

To solve these equations it is assumed that the horizontal, vertical and rotational displacements of the cross section, consist of a time dependent and a time independent part. Only the time dependent solution is sought to determine dynamic instability and to do this the partial differential equations are rid of the time independent terms. The auxiliary boundary conditions derived by modifying the actual boundary conditions to suit the modified differential equations are substituted in the solutions of these (obtained by classical methods) which are obtained in terms of S, a complex variable.

The complex values of S, satisfying the solution and having positive real parts indicate stretched string vibrations which increase in amplitude exponentially with time, that is such values indicate negatively damped and self excited vibrations. The positive real roots can be identified by using the usual Routh's criterion.

Once it has been established that such roots exist, it remains to find them out. They will specify the frequency and rate of build up of instability. The root solving is a complicated process, but using the numerical analysis technique a fairly accurate solution can be found.

Simpson's paper(36) sets up the approximate equations of motion of single span transmission line employing the principle of virtual work. By means of matrix notation used the theory can be extended for multispan lines. Instability is again identified by Routh's criterion applied to the solution. It is difficult to compare the relative merits of the two papers, each being equally useful in its own way. There seems to be more rigour in the latter and the criterion developed are complex. It does not lend itself easily to application to every individual span, because of the amount of labour involved. Calculations by long hand methods are virtually impossible and digital computer study must be resorted to.

Mathowski's paper(31) gives the quantitative relations for the internal energy dissipation of stranded conductors - an aspect hitherto neglected. It should be useful in the design and coordination of the vibration schemes when they are available. For galloping however no successful damping scheme has so far been designed, the energy associated with it being too large to be spent in any dissipative apparatus. Cure is impossible, prevention needs more investigations. This paper also deals with the wind energy inputs to galloping spans, the computation being done from the data available from wind tunnels. An element of length of the conductor is considered and the instantaneous vertical component of the lift and drag forces (obtained by wind tunnel experiments) is integrated over the distance travelled as the conductor moves through one cycle yields the wind energy input to the element. Another integration of the energy input over the entire span will result in the total energy input to the span in one cycle. A method is suggested to perform this double integration by what is called as the use of non dimensional quantitites.

Another important contribution of the paper is the determination of the general characteristics of the torsionally modified and torsionally controlled galloping in addition to the usual torsion free galloping, an aspect on which rather scant information is available.

CHAPTER - 4

FIELD STUDIES - INSTRUMENTATION

4.1 General

The importance of the experimental investigation of the vibration phenomenon can not be too highly emphasised. After everything is said and done it remains a fact that the theoretical analysis of this subject is far from being rigorous in every aspect, and is based on many assumptions made from time to time to simplify the work involved. Even the simplest of dampers namely the stockbridge damper considering all its modes of vibrations, degrees of freedom, natural frequencies mechanical reactances etc. presents a formidably complex mathematical exercise and its analysis without assumptions and simplifications would be virtually impossible. As such any predictions regarding vibration phenomena in general would be incomplete without experimentation as a means of probe as well as varification.

The experimental work in mechanical vibrations studies of overhead conductors can be broadly classified into:

1) Field studies or outdoor studies.
2) Laboratory studies.

The former can be split up into long term or extended studies and short term studies. The latter can be further classified into :

1) The wind tunnel studies.
2) The model studies with artificial mechanical excitatio
3) The analog studies.

In this chapter the outdoor or field tests will be studied while the remaining ones will be dealt with in the following chapters.

The long term outdoor studies consist of observation of the dynamic behaviour of the conductors over an extended period of time which may be several months and even an year or more. The data are recorded periodically for a short duration care being taken that conspicuous behaviours do not escape attention. These data may be collected in the form of oscillographic records or in tabular form but the former is more usual. After the entire data is obtained it is reduced by eliminating the inconspicuous and less important parts and then analysed to obtain a generalizable conclusion and also for verification of theoretical predictions for those particular spans if any have been made. These studies are very laborious, take a lot of time and are rather expensive. Often it happens that the effort involved in reducing and analysing the data is entirely out of proportion to the value of the results obtained. But they are indispensable in the sense that without them the vibration analysis is a mere blind search. Care and prudence have therefore to be exercised in selecting the site, terrain, spans, weather condition etc. such that there is a very minimum of unnecessary data.

Short term studies are rather less informative because they do not in general, reveal the most severe combination of vibration conditions that are encountered on the line. They are a sort of compromise between the expensive and tedious long term tests and the finances and time allowed. In particular cases however they may be as important as any other

These studies, it hardly need be emphasised, are conducted for both the aeolian vibrations and galloping separately.

4.2 Choice of Site and Season for Vibration Tests

It is obvious that only such spans of the transmission lines are chosen for study as are most susceptible to vibration damage. Aeolian vibration is generally present, in all the spans that are strung at a tension of more than about 10 per cent of their ultimate strength for anything between 60 to 80 per cent of the time. Severe frequencies and amplitudes are found when tensions are high and wind speeds rather low because as the wind speed increases the Reynold number (R = 6380 V.d) increases and when this value is greater than about 200 000 the disturbance in the conductor wake becomes random and turbulent with the effect that the periodicity of the alternating force also becomes random and resonance does not stay. The weather is not important in other respects (temperature, rain and snowfall etc.) in these kind of studies.

The most important spans that provide very valuable information in galloping studies are the long river crossings. In these the dancing is very severe and troublesome. This is because tensions in these cases are high (25 per cent or more of the ultimate strength) and this in the first place reduces the internal damping of the conductor due to interstrand friction. Also the length of the river puts a greater dissipative load on the damping apparatus at span ends than in the normally shorter over land spans. This is because as the span length increases the power from wind also increases in direct proportion. (Higher tensions have another disadvantage, they not only encourage higher frequency of vibration and a greater number of fatigue cycles per unit time but may also result in more flexure of the cable in each cycle). The galloping as has been said earlier occurs mostly in cold climate in winter after a snow fall and is rather infrequent. All these considerations must be kept in mind whilst selecting a site for vibration field study.

4.3 Instrumentation

The quantities to be measured in the galloping or aeolian vibration outdoor tests are more or less the same, the only difference being in the magnitude of the data in the two cases and the ranges of the instrument required. The general data required is as under :

(a) Conductor Vibration data

1) Amplitude or displacement; both translational and rotational.
2) Frequency.
3) Loop length.
4) Conductor velocity.
5) Strain.

(b) Meteorological data

1) Wind speed and direction.
2) Normal Wind Velocity.
3) Barometric pressure.
4) Humidity.
5) Atmospheric temperature.

(c) Associated data

1) Conductor temperature.
2) Conductor tension.
3) Clamp movements.
4) Damper movements.

Besides these there may be many other quantities to be measured depending on the object of the particular experiment.

All these quantities can be measured by the conventional instruments. The drawback however is that rugged outdoor type instruments of conventional principle and design,with adequate precision and sensitivity, as are required for these field studies, are rare and not easily available. However with the introduction of electronic instruments and electric transducers this need is fulfilled to a great extent. The conventional and special instruments both are discussed in the following paragraphs.

4.31 Amplitude

A wide variety of instruments is available for the measurement of amplitude. In general the various investigators have designed and fabricated their own type of vibration recorders. There are first mechanical recorders which produce oscillographic records of the oscillation on a reduced scale on smoke paper or a wax coated chart turned by mechanical clock movement by suitable strings, lever and stylus arrangement(24). Records by means of high speed cine cameras also have been obtained on films (by mounting a target on the conductor and photographing from ground, later applying optical corrections for the angle included between axis of the camera and the plane of movement of the target). By this means (cine films) the records can give both the translational motion and rotational motion which are useful for galloping studies(16). Recently a new type of vibration recorder has been devised(32) which is of a simple and rugged design, is capable of being installed on energized conductor without removing them from service and produces amplitude and frequency records on a cellulose tape which does not require any chemical processing. The resulting records can be analysed by eye immediately after a test (

.

The amplitude or displacement can also be telemetered by electric transducers. First the velocity of the conductor is measured by velocity pick ups (self generating transducers) and then the displacement is obtained by integration of the output of these pick ups by simple integrating circuits.

The Bonville Power Administration and the Aluminium Company of America have in the past developed vibration recorders which had been use for a pretty long time(24) but now are replaced by modern electric transducers and other recorders.

4.3.2 Frequency

The simplest type of frequency counter is the Jacquet cycle counter which totalizes the number of vibration cycles above a certain base amplitude level (which can be adjusted) occuring within a narrow frequency range (which includes all normal vibrations of the conductors). The actual frequency of course has to be worked out by dividing the number of cycle recorded by the duration of the interval. From the oscillographic records produced by any of the instrument also the frequency can be worked out similarly.

The present trend however is to measure the frequency from the oscillographic records produced by the strain gauges (strain - undergoes a cycle of reversal in one cycle of conductor oscillation). An old and popular method has been to use an inertial mass and a switching arrangement on the amplitude measuring arm of the recorders to produce d-c. pulses through an R-C circuit.

For the use of vibration protection criterion based on the maximum permissible rates of vibrations (Mc/year) the Jacquet cycle counter is still the best as it is handy, light can be used on live lines and is very cheap.

There are many types of handheld vibrometers. These provide instantaneous readings only and therefore their usefulness is limited in application. They offer no way of determining the duration of vibration or whether the sampling represents a maximum, minimum or average condition.

4.3.3 Conductor Velocity

The only method of directly metering the velocity of the conductors is by means of the self generating type transducers used as velocity pick ups. Indirectly it can be measured from the amplitude and frequency data.

4.3.4 Stresses and Strains

By far the most accurate present method of determining the cyclic stresses in conductor strands is the use of resistance type strain gauges cemented to the strands near the end of the suspension clamp. They form one arm of a Wheatstone's bridge circuit. The strain gauge element which undergoes the same strain as the strand it is connected to has a direct relationship (linear) between its resistance and strain. By measuring the resistance on Wheatstone's bridge circuit the s strain can be calculated and thus the stress. The electrical leads from fixed arms of Wheatstone's bridge are brought out to an amplifier and oscillograph for oscillographic records. Prior calibration is then necessary. The principal disadvantage of the strain ~~gau~~ gauge technique is that line must be deenergised for these tests.

4.3.5 Normal Wind Velocity

Usually the more important quantity to be measured in the meteorological data is the components of the wind speed which is normal to the conductor and this is obtained by compounded anemometers with direction vane driven sine potentiometer.

4.3.6 Wind Speed and Direction

Wind gauges as used in the aeronautics are quite suitable for these experiments. Oscillographic records which are required can be produced with these.

4.3.7 Barometric Pressure and Humidity

In the interest of portability and ruggedness the conventional instruments are discarded and special transducers (potentiometer type for pressure and Wheatstone Bridge type for humidity) are used.

Atmospheric temperature in fields is measured by thermistors or thermocouples for the convenience of oscillographic recording.

4.3.8 Conductor temperature

This is measured by thermistors.

4.3.9 Tension

For measurement of tension there are various types of instruments available. To mention only one, the load cell is quite frequently used. However commercially available instruments serve the purpose eminently.

The movements of clamps and dampers are measured by the commercially available accelerometers.

4.4 Mobile Laboratories

For an exhaustive field study of the dynamic physical behaviour of the conductors it is essential that data be collected for a number of spans for a prolonged period simultaneously. This requires that either a great amount of duplicate instrumentation be installed on a fairly permanent basis at a number of representative spans over the entire length of transmission lines or that a single instrumentation package complete with operating crew and all necessary equipment and facilities for extended operation be housed in an easily transportable unit to provide the high degree of mobility necessary to obtain data from a variety of geographical regions and remote locations. Many attempts to build such laboratories have been made-a good and successful example of these is the Dynalab (trade name given to the mobile vibration laboratory unit) made by the Preformed Line Products Company of Cleveland, Ohio, U.S.A.(25). It has a very sophisticated instrumentation system constructed in it for accumulating data in field studies by telemetry. With a little care it is capable of extracting data from live H.T. conductors without disturbing the continuity of supply.

CHAPTER - 5

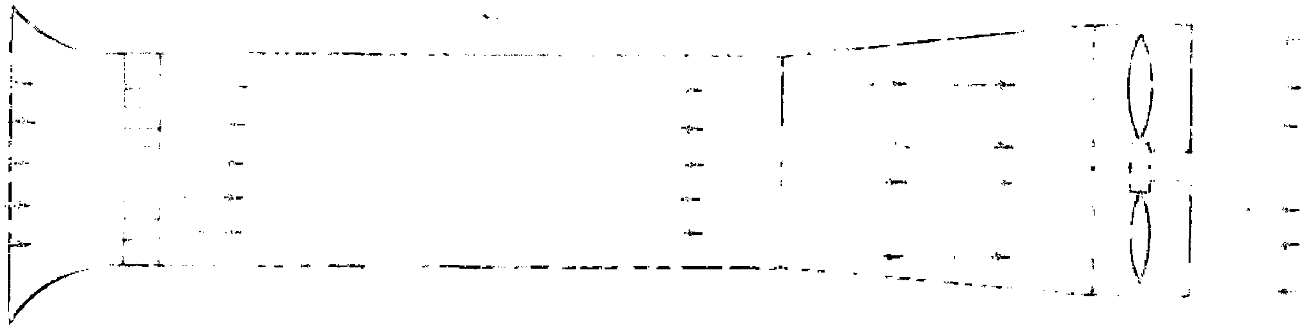
WIND TUNNEL MODEL STUDIES - AERODYNAMIC BEHAVIOUR

5.1 Introduction

A very enlightening and critical study of the vibration phenomenon can be made in the wind tunnels which are generally used for aerodynamic experiments. The facility of varying most of the vibration parameters which the wind tunnel. affords, makes it a very valuable piece of equipment. Many of the important conclusions about conductor vibration phenomenon have either been directly drawn from wind tunnel tests or confirmed through them.

5.2 Description

In essence the wind tunnel consists of, as the name implies, a tunnel of suitable size through which air can be made to flow at a controlled velocity by means of impellers driven by variable speed motors. A uniform velocity is obtained over the entire cross section of the test section of the wind tunnel by suitable design. In practice there are two kinds of wind tunnels, namely; open circuit and the closed circuit type. In the first, air is drawn in from one end of the tunnel from the atmosphere, forced through the tunnel and let off at the other end. In the closed circuit tunnel however the same air is circulated in the tunnel over and over again through a closed path. By this means a control can be exercised on the temperature and pressure of the circulated air if the exigencies of the experiment demand it. For most of the conducto



[illegible] Open circuit [illegible] tunnel.

vibration experiments, the open circuit wind tunnel is quite entirely adequate. Use of closed circuit wind tunnels has so far not been reported in the existing literature on this subject. A schematic sketch of a common wind tunnel is shown in Fig. 8.1.

8.3 Test Models and Testing Methods

For the study of the vibration of any prototype outdoor test span its model geometrically scaled down from it is mounted inside the wind tunnel at desired angle to the wind stream. The wind velocity is varied over the range required (which is usually between 0-80 m.p.h., the lower part of the range used for aeolian vibration and the upper part for galloping) and the response of the test span recorded. The quantities usually recorded or computed are : amplitude, frequency, logarithmic decrement, stresses and strains at the supporting structure, energy input from the wind and the aerodynamic properties of the wind such as wind speed, direction (angle of yaw), Reynolds number, Strouhal number etc. A record of the barometric pressure, temperature and humidity may also be necessary in the final analysis. From the aerodynamic correlation equations the observations actually recorded for the model can be transformed to give the response of the regular outdoor prototype transmission line span under the existing conditions. The effect of vibration suppressing schemes can also be studied in the wind tunnels.

In an ingenious method(17) of wind tunnel study of conductor vibration, instead of a complete model of the span with its proportionately scaled down end attachments, only a small section (about 70 inches) of the model is mounted inside the wind tunnel attached at the middle of suitable vertical coil springs at either end. In this way due to vortex discharge in the conductor wake the whole model vibrates with a constant amplitude all along its length. As this model is considered to be only a small element of the vibrating span, the results thus obtained can easily be extended to cover the entire span by a simple process of integration. For example if the energy imparted by the wind to the vibrating span is to be calculated, and a model whose cross section, profile, weight, etc. are directly scaled down from the prototype (not necessarily, however, the mass radius of gyration if no coupling between translational and rotational motion is assumed.) is used for wind tunnel study, thenthe air forces on the model represent to the correct scale the air forces on the prototype at the corresponding amplitude and therefore the ratio of energy transfer per unit length is identical on model and prototype at equivalent scaled amplitudes. The overall ratio of energy transfer (energy transferred in one cycle divided by the total energy of vibration of that cycle) on the prototype where amplitude is not constant along the length is determined by the summation of energy transfer on all the unit lengths, each moving at its and amplitude or in other words by integration.

5.4 Fabrication of Models

The actual conductors that are generally used on prototype spans can rarely be used as models in their natural conditions. The smaller ones usually lack stiffness and the excitation arising is weak as also sagging etc. may cause the amplitude to be non uniform. The larger ones besides having inadequate stiffness are too heavy to show any worthwhile response. Because of these reasons geometrically scaled models the mass stiffness etc. of which have been brought to the level of the requirements of the experiment, are necessary.

Stranded conductors can be replaced by a model constructed of light aluminium tubes coiled around a straight section of tubing, taking care to see that the pitch remains same in the laying of the coil. Relative motion between the various tubes has to be avoided as it gives rise to undesirable damping and this can be done by filling the inner tube and the spaces between the tubes with some light cementing material. Plaster of Paris can serve this purpose admirably.

Smooth circular conductors can be replaced by a smooth aluminium tubing without difficulty. In all these cases in the interest of stiffness the model cross section usually has to be kept larger than the actual cross section of the prototype.

6.6 End Attachments

Spring suspension can be used as the end attachment in the type of experiment described.Some frequency of vibration is in a way controlled by the spring suspension and therefore its design is dependent on practical considerations of each case. However there is no exact method available for design and a large latitude is available the limits of spring characteristics being established by the steady wind velocity range in the wind tunnel.

6.6 Correlation Equations

Function	Symbol	Scale factor
Diameter	d	$\frac{d_m}{d_p} = n$
Weight, unit	w	$\frac{w_m}{w_p} = n^2$
Weight total	W	$\frac{W_m}{W_p} = n^3$
Frequency	f	$\frac{f_m}{f_p} = \frac{1}{\sqrt{n}}$
Wind velocity	V	$\frac{V_m}{V_p} = \sqrt{n}$
Displacement	y	$\frac{y_m}{y_p} = n$

The suffix m stands for model and p for the prototype. These scale factors for correlating model behaviour with the prototype are arrived at from aerodynamic considerations and can be assumed.

6.7 Instrumentation

The normal wind tunnel instrumentation is used for registering the properties of the wind. The frequency and amplitude of vibration can be measured from oscillographic record produced by electrical pick ups mounted on the conductor. It is usually desirable to calibrate the instrumentation before hand and then take the errors into account.

contd.

5.8 Importance of the Uniformity of Wind Over the Models, Boundary Layer Effect

Care should be taken to see that the velocity remains constant and uniform over the length of the model. Turbulence in the wind gives rise to errors which can not be satisfactorily taken into account.

To ensure that the errors due to boundary layer effect are not introduced in the data collected, the ratio of the height of the wind jet to the diameter of the conductor should always be greater than 12 (Ref. 17).

CHAPTER - 6

LABORATORY STUDIES - AUTOMATIC VIBRATION CONTROL

6.1 General

The laboratory studies of conductor vibration form another important part of the general investigation. Though by and large the schemes employed for these investigation principally are same as in other type of tests there is a difference in the set ups and certain other specific aspects. Unlike the field tests only a sealed model of the span is tested for vibration endurance while difference from the wind tunnel studies lies mainly in the method of producing or inducing vibrations. In laboratory scale models the variable velocity air stream of the wind tunnel is replaced by artifical means of excitation which may consist of mechanical or electromechanical shakers. The instrumentation used in there, is not far different from that used in other tests in principle ; but because the tests are conducted in door, less sophisticated instruments can be used without sacrificing precision. Even the conventional instruments without refinement in ruggendness and weatherproofing can perform their function admirably. The live line instruments are unnecessary and so are the electric transducers used for telemetry(accessibility of the model being high).

6.2 Purpose of the Studies

The purpose of the laboratory studies is usually to determine the stresses and strains at the supporting structure and the points of attachment of other line hardware to the conductor, and to assess their ability to withstand fatigue. Efficacy of vibration suppressing schemes of new designs or principles is also first studied in the laboratory with simulated vibration conditions. Accelerated aging tests also conducted in the laboratories, serve to determine the normal operating life of conductors for various values of tensions and also for the different types of clamps and accessories which include the vibration suppression schemes. Improvements in the design of these can be suggested after thorough laboratory studies. Predictions regarding selective damping etc. can also be made after these tests. Broadly, the object in these studies is to form a sort of preliminary investigation to supplement the data received from other types of studies.

6.3 Set Ups

Unlike the wind tunnel studies (though they may also be considered as laboratory studies) for these the general laboratory set ups consists of a model of the complete span. (In the former only a section of the span is studied). As far as possible for the purpose of these studies the model span end attachments have to be simulated to the actual line supports to incorporate same amount of flexibility and freedom of movement. However this may not always be possible and as a first approximation then, rigid supports are used. It is often required to change the tensions in the line model and then one end attachment or support has to be a pulley over which the conductor is taken. At this end of the conductor weights are attached the tension being varied by adjusting their weights.

6.4 Actuators

The span models thus erected have to be vibrated to resonance to make observations and collect data. Wind is not a controlled factor as is in the wind tunnels - in fact all the laboratory studies are done in still air. Evidently therefore, there is a need to actuate vibration artificially. There are a number of types of mechanical actuators or shakers. The eccentric flywheel placed in contact with one end of the wire has been a common arrangement. Due to its eccentric rotational motion, it gives periodic impulses to the wire and the frequency of these impulses can be varied by adjusting the speed of the motors, which drive these flywheels. The natural frequencies of the span model would be those at which it vibrates with maximum amplitude. With this set up, in the first place, the frequency response of the system can be studied. The present trend in the actuators however is to employ electromechanical transducers to which variable frequency output is given by electronic oscillators. The vibrations are then sustained in a method similar to those of an electrically driven tunning fork.

6.5 Study of Dampers

For studying the efficacy of the dampers various investigators have employed different technique. As a typical example the experiments conducted for the study of the 'single degree of freedom' damper as reported in ref. 30 can be cited. The set up was as under.

In these, the conductor is simulated by a short metal rod and the damper is attached to it. Another rod welded perpendicular to the simulated conductor passes through an oversized clearance hole drilled in the damper casing and is attached to an electrodynamic vibration exciter below. The exciter vibrates the simulated conductor throughout the amplitude and vibrations range encountered under field conditions. The mechanical impedance of the damper for sinusoidal motion is measured with a special type of impedance head measures simultaneously the force applied to the damper and the resulting acceleration. The magnitude and the phase of the force and acceleration outputs of the impedance head are measured on voltmeters and dual beam oscilloscope. The velocity can be measured by integrating the acceleration output by simple integrating circuits. The mechanical impedance values expressed as the ratio of force to velocity are functions of frequency. They give measure of the efficacy of the damper at various frequencies because as explained in deep chapter 9 the real part of the impedance function is responsible for all the dissipation of the vibration energy in the damper.

The other important study is that of the damper life. Following the specifications laid down by the standards institutes for testing of materials, accelerated aging tests are conducted. Thus in this particular example the neoprene filling of the sponge damper (see chapter 8) soaked at

212°F for upto 30 days simulates 30 years of outdoor exposure. The tests as before, are conducted after accelerated aging and performance of the damper observed. Dampers and other accessories are expected to have a normal service life of 20 - 30 years.

6.6 Analog Studies

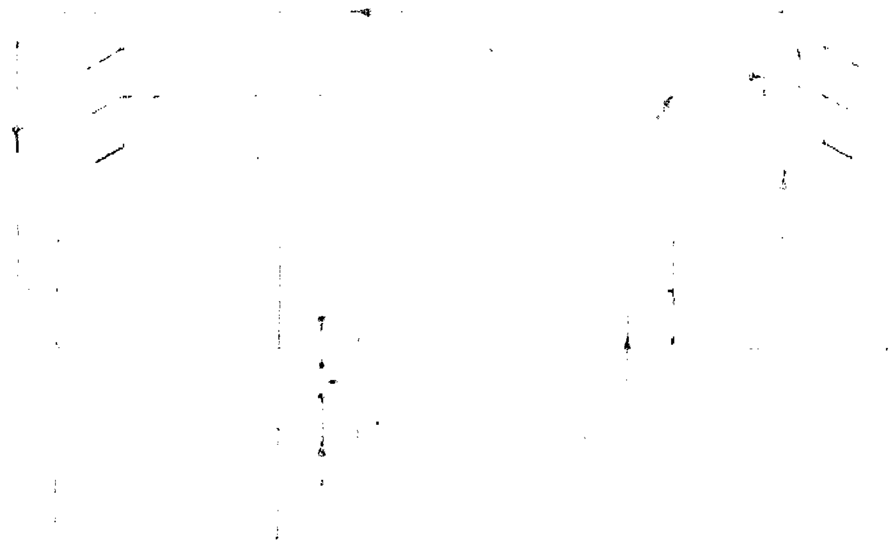
With electromechanical analogies as explained in chapter 9 the vibration studies are very much simplified. Electrical ladder or equivalent networks are built to simulate the vibrating conductor the damper being replaced by lumped impedance. The response of the analog model to an alternating voltage which represents the wind force is recorded as a current (which represents the velocity of the conductor or the damper) in the appropriate branch of the network. Power loss in the lumped element represent the damper dissipation - a measure of its effectiveness. All these quantities are very easy to record oscillographically with required precision unlike the mechanical measurements. Also the set up is much less cumbersome or unwieldy.

A more complete explanation of electromechanical analogies will be found in chapter 8.

6.7 Automatic Electronic Control.

According to modern trend in the laboratory studies of the conductor vibration, precision is sought to be introduced by what is called as the automatic electronic control of these vibrations. In the vibration produced by electromechanical means the frequency at which the conductor


K



is driven is usually determined by a variable frequency electronic oscillator, initially set so that operating frequency corresponds to a natural mode of vibration of the test conductor. With the conductor vibrating in a resonant mode the amplitude of vibration is adjusted to the desired level by gain controls on the amplifiers which drive the electromechanical transducers. Such a system is illustrated in Fig. 6.1 by a block diagram.

In this method of operation, the driving frequency is determined by the variable frequency oscillator and is essentially constant, any changes in the natural frequencies of the test conductor due to changes in length, tension, ambient temperature, fatigue effects and vibration amplitudes, will force the sample into non resonant vibration.

When the driving mechanism is essentially a constant r.m.s. force device, as are most electrodynamic shakers, deviation from resonant frequency operation is invariably accompanied by significant reduction of the vibration amplitude. For constant amplitude operation, continual operator supervision of equipment is required for compensating manual adjustment of oscillator frequency and gain.

6.7.1 Frequency Control

The main requirement of automatic control in such a case is a system in which the controlled frequency varies in accordance with conductor conditions to maintain resonance. This can be accomplished by deriving a control voltage from a vibration pick up mounted on the test conductor at the point of attachment of driving transducer. By judicious control of the magnitude and phase of the vibration pick up signal, it can be synchronized with the signal from the variable frequency electronic oscillator controlling the conductor vibration. When this condition exists, the vibration pick up signal can be substituted for that of the oscillator without affecting vibration conditions. The entire system is then operating in a self excited oscillatory manner as indicated in Fig.6.8. Electrical signals controlling the vibration travel through the system over the path shown and in the direction indicated by arrows.

The mechanics sustaining the vibration can be more fully understood by consideration of conditions existing at resonance. When a system is driven by external force, resonance is the condition when response is maximum but a more basic condition is when the excitation (force) and response (velocity) are in phase.

When energy loss of the vibration is small compared to the energy stored per cycle, these two conditions occur simultaneously. At higher than resonant frequencies force leads that velocity and lags for frequencies lower than resonant ones. The force produced by the electrodynamic transducer is in phase with current flowing in its windings, which at a given frequency varies by a constant angle from the phase of the input control voltage which may be from the oscillator or from the vibration pick up itself.

To obtain a transducer force in phase with conductor velocity it is necessary to shift the phase of pick up signal properly. When this signal replaces the oscillator output any downward shift in the natural conductor frequency will cause the phase angle of the velocity to lag momentarily behind that of the driving force. However since the modified signal is in phase with the velocity and determines the force of the shaker, a correction of overall system frequency is automatically instituted to return the force and velocity to phase agreement and resonance is maintained.

6.7.2 Amplitude Control

The power required to drive a conductor to a specific amplitude of resonant vibration varies as the resonant frequency shifts and hence means must be provided for maintaining a separate amplitude control on the test specimen. This can be done by maintaining the overall system amplification to a value expressed as

$$g = K \int_0^t (Er - Ev)\, dt.$$

where g = system gain

K = A preset constant determining the response speed of amplitude correction

Er = Reference voltage

Ev = Voltage proportional to average value of test conductor vibrations amplitude.

The voltage Ev is derived from the vibration pick up by rectification and filtering. The reference voltage Er is adjustable, its magnitude determining the stabilised -

vibration level. Operation is then sustained at an amplitude for which Er = Ev. Whenever Ev is less than Er the error voltage is positive. This is applied to an electronic integrating circuit whose output controls the gain of the amplifier. When the integrand is positive, the value of the integral will shift to more positive values.

There fore when actual amplitude is less than the desired amplitude (Ev<Er), the amplitude will increase at a rate determined by K and the difference (Er - Ev). This increase is accompanied by an increase in the magnitude of Ev causing the value of the integrand (Er - Ev) to approach zero thus the rate of correction is reduced as the actual amplitude approaches the desired preset level.

These kinds of automatic electronic control can be used for actual overhead transmission test spans also.

CHAPTER - 7

QUANTITATIVE RELATIONSHIPS

In this chapter are given some of the more important relationships which are helpful in computing or specifying the forces acting on the conductor (useful for stability analysis), the stresses and strains at the clamps etc., the energy imparted to spans and their inherent dissipation. References have been given to the sources from where they have been taken. Proofs of these are not given because, they can be easily obtained from the references cited. The relations for frequency etc. which have been derived while explaining the mechanism of the phenomena in chapter 2 are not given here to avoid repetition.

7.1 [illegible] (29)

7.1.1 Inertial forces (These act through the centroid.)

Inertial force in x direction

$$= - m.s. \frac{d^2}{dt^2} (y + \theta.C_x) \qquad --- \quad 7.1$$

Inertia force in y direction

$$= - m.s. \frac{d^2}{dt^2} (x - \theta.C_y) \qquad --- \quad 7.2$$

Inertia torque, total, (about shear centre)

$$\begin{aligned} &= - m.s. \frac{d^2}{dt^2} (y + \theta.C_x) .C_x \\ &\quad + m.s. \frac{d^2}{dt^2} (x - \theta.C_y) .C_y \\ &\quad - m.I_p \frac{d^2}{dt^2} (\theta) \qquad --- \quad 7.3 \end{aligned}$$

The third quantity being due to rotational inertia and the first two the torque contribution due to the two inertia forces.

7.1.2 Viscous Friction Forces

In x direction

$$= - f.\frac{\partial}{\partial t}\left(y + \theta.C_x'\right) \qquad --- \quad 7.4$$

In y direction

$$= - f.\frac{\partial}{\partial t}\left(x - \theta.C_y'\right) \qquad --- \quad 7.5$$

Viscous Friction Torque (about shear centre)

$$= - f.\frac{\partial}{\partial t}\left(y + \theta.C_x'\right).C_x'$$

$$+ f.\frac{\partial}{\partial t}\left(x - \theta.C_y'\right).C_y'$$

$$- f'.\frac{\partial}{\partial t}(\theta) \qquad --- \quad 7.6$$

The third quantity being due to rotational motion and the first two, the torque contribution due to the two viscous friction forces.

7.1.3 Component of Tension in x Direction

$$= T.\frac{\partial^2}{\partial z^2}(y) \qquad --- \quad 7.7$$

Component of tension in y direction

$$= T.\frac{\partial^2}{\partial z^2}(x) \qquad --- \quad 7.8$$

Torque about shear centre due to these

= 0 as they act through shear centre.

7.1.4 Aerodynamic Forces (acting through the aerodynamic centre)

$$\text{Lift} = -C_L \,.\, b \,.\, \rho \,.\, v^2 \,.\, \alpha \qquad --- \quad 7.9$$

$$\text{Drag} = C_{Do} \,.\, b \,.\, \rho \,.\, v^2 + C_D \,.\, b \,.\, \rho \,.\, v^2 \,.\, \alpha \qquad --- \quad 7.10$$

These forces are perpendicular to the relative wind and in the direction of the relative wind respectively. Approximately the components of these;

In x direction

$$= -C_L.b.\rho.v^2.\theta - \left[C_L.b.\rho.v + C_{Do}.b.\rho.v\right]\frac{\partial y}{\partial t} \qquad --- \quad 7.11$$

In y direction

$$= C_{Do} \,.\, b \,.\, \rho \,.\, v^2 + C_D \,.\, b \,.\, \rho \,.\, v^2 \,.\, \theta + C_D \,.\, b \,.\, \rho \,.\, v \,.\, \frac{\partial y}{\partial t} \qquad --- \quad 7.12$$

The torques due to these forces are

$$-\left[C_L \,.\, b \,.\, \rho \,.\, v^2 \,.\, \theta + (C_L \,.\, b \,.\, \rho \,.\, v + C_{Do} \,.\, b \,.\, \rho \,.\, v)\frac{\partial y}{\partial t}\right] \times c_x'' \qquad --- \quad 7.13$$

and

$$\left[C_{Do} \,.\, b \,.\, \rho \,.\, v^2 + C_D \,.\, b \,.\, \rho \,.\, v^2 \,.\, \theta + C_D \,.\, b \,.\, \rho \,.\, v \,.\, \frac{\partial y}{\partial t}\right] c_y'' \qquad --- \quad 7.14$$

7.1.5 Torque Resisting the Twist in the conductor

$$= G \, . \, I_p \, . \, \frac{\partial^2}{\partial z^2} \, (\theta) \qquad --- \qquad 7.15$$

7.2 Stresses and Strains, Deflection, Bending Moments etc.(27)

Basic beam equation for bending is

$$= E \, . \, I \, . \, \frac{d^4 y}{dx^4} - H \, . \, \frac{d^2 y}{dx^2} + w = 0 \; --- \; 7.16$$

Complete solution for the origin taken at the point of suspension is,

Deflection

$$y = \frac{P}{2H} \sqrt{\frac{(E.I)_o}{H}} \left[\text{Sinh} \sqrt{\frac{H}{(E.I)_o}} \, . \, x - \left(\text{Cosh} \sqrt{\frac{H}{(E.I)_o}} \, . \, x - 1 \right) \right] - \frac{P.x}{2H} + \frac{w.x^2}{2H} \qquad --- \qquad 7.17$$

(Suffix o stands for the entire cable, suffix s for strand)

Slope

$$\frac{dy}{dx} = \frac{P}{2H} \left[\left(\text{Cosh} \sqrt{\frac{H}{(E.I)_o}} \, . \, x - 1 \right) - \text{Sinh} \sqrt{\frac{H}{(E.I)_o}} \, . \, x \right] + \frac{w.x}{H} \qquad --- \qquad 7.18$$

Bending Moment

$$M = (E \, . \, I)_o \; \frac{d^2 y}{dx^2}$$

$$= \frac{P}{2} \left[\sqrt{\frac{(E.I)_o}{H}} \; \text{Sinh} \sqrt{\frac{H}{(E.I)_o}} \, . \, x \right.$$

$$- \operatorname{Cosh} \sqrt{\frac{H}{(E.I)_o}} \; . \; x \Big]$$

$$+ \frac{w}{H} \; (E.I)_o \qquad --- \qquad 7.19$$

<u>Shear</u>

$$V = (E.I)_o \; \frac{d^3y}{dx^3}$$

$$= - \frac{P}{2} \left[\operatorname{Cosh} \sqrt{\frac{H}{(E.I)_o}} \; . \; x - \operatorname{Sinh} \sqrt{\frac{H}{(E.I)_o}} \; . \; x \right]$$

$$--- \qquad 7.20$$

The stress in the outermost strand in terms of the radius of curvature ρ

$$\sigma = E_o \; . \; \frac{ds}{2} \; . \; \frac{1}{\rho} \qquad ---- \qquad 7.21$$

Corresponding strain in the outer strands

$$= \frac{E_o}{E_s} \; . \; \frac{ds}{2} \; . \; \frac{1}{\rho} \qquad ---- \qquad 7.22$$

Where the radius of curvature is given by

$$\rho = \frac{1}{\frac{d^2y}{dx^2}}$$

Equation of motion of the vibrating cable

$$-\frac{\partial V}{\partial x} . dx + H \frac{\partial^2 y}{\partial x^2} . dx = m . dx . \frac{\partial^2 y}{\partial t^2} \qquad --- \quad 7.23$$

The final form of this equation after proper substitution

$$(E.I)_o . \frac{\partial^4 y}{\partial x^4} - H . \frac{\partial^2 y}{\partial x^2} + m . \frac{\partial^2 y}{\partial t^2} = 0 \qquad --- \quad 7.24$$

Solution of this equation is

$$y = X(x) . T(t) \qquad --- \quad 7.25$$

where

$$T(t) = A \operatorname{Cos} \omega . t + B. \operatorname{Sin} \omega . t \qquad --- \quad 7.26$$

and

$$X(x) = K_1 . \mathcal{E}^{+\lambda x} + K_2 . \mathcal{E}^{-\lambda x} + K_3 . \mathcal{E}^{+k x} + K_4 . \mathcal{E}^{-k x}$$

also $= C_1 \operatorname{Cos} \lambda x + C_2 \operatorname{Sin} \lambda x + C_3 \operatorname{Cosh} k x + C_4 \operatorname{Sinh} X . x$

where

$$\lambda^2 = \left[\frac{H^2}{4(EI)_o^2} + \frac{m \omega_n^2}{(E I)_o^2} \right]^{\frac{1}{2}} + \frac{H}{2(E I)_o}$$

$$k^2 = \left[\frac{H^2}{4(E I)_o^2} + \frac{m \omega_n^2}{(E . I)_o^2} \right] - \frac{H}{2(E I)_o}$$

A, B, K_1, K_2, K_3, K_4, C_1, C_2, C_3 and C_4 are arbitrary constants

--- 7.27

For pinned - partially pinned boundary conditions with a degree f fixing = 1 - ξ (See chapter 3)

Boundary conditions at x = 0 are $y = ~~X~~ X_n(0) = 0$

and $(E.I)_o . \frac{d^2 X_n}{dx^2} = (1 - \xi)(Mc)_{x=0}$

and at x = ℓ

$$y = X_n(l) = 0$$

and $$(EI)_0 \frac{d^2 X_n}{dx^2} = 0 \Bigg]$$

Solution of the equation is

$$X_n = C_2' \tan \lambda_n l \left[\frac{\sin \lambda_n x}{\tan \lambda_n l} - \cos \lambda_n x + \cosh k_n x - \frac{\sinh k_n x}{\tanh k_n l} \right]$$

The suffix n denotes that the quantity is for the n th natural frequency

The maximum strain caused by dynamical loading

$$\epsilon_{b\,max} = \pm \frac{d_c}{2} \left[\frac{d^2 y}{dx^2} \right] \qquad \text{--- 7.29}$$

$$= \pm C_2' \frac{d_c}{2} \tan \lambda_n l \times \left[\lambda_n^2 \left(\cos \lambda_n x - \frac{\sin \lambda_n x}{\tan \lambda_n l} \right) + k_n^2 \left(\cosh k_n x - \frac{\sinh k_n x}{\tanh k_n l} \right) \right]$$

--- 7.30

7.3 Energy input from wind(17)

The expression which can be used to determine the energy imparted to a vibrating conductor whose oscillographic records have been obtained by wind tunnel tests is

$$E_a = \frac{1.356\ W \cdot \pi^2 \cdot f^3 \cdot \delta_a \cdot \eta}{72 \cdot g} \text{ Watts} \qquad --- \quad 7.31$$

where η is the amplitude of vibration.

δ_a is the Logarithmic decreament due to the air forces on the conductor, considered positive when the amplitude increases with time.

If η_n is the amplitude in the n^{th} cycle and η_{n+1} in the $(n+1)^{th}$ cycle then

$$e^{\delta a} = \frac{\eta_{n+1}}{\eta_n} \qquad --- \quad 7.32$$

The logarithmic decreament itself has been found to be a function of the maximum amplitude

$$\delta a = A + B \cdot \eta_m + C \cdot \eta_m^2 \qquad --- \quad 7.33$$

Where A, B and C are constants for a particular conductor. If from experimental tests these values are worked out, then the final equation for the energy input due to wind has been shown to be equal to

$$E_a = 320 \cdot 940 \left(\frac{W}{d2}\right) \cdot A \cdot \eta^2 + 170 \cdot 264 \left(\frac{W}{d}\right) \cdot B \cdot \eta^3$$

$$+\ 94 \cdot 025\ (W) \cdot C \cdot \eta^4 \text{ Watts} \qquad --- \quad 7.34$$

Farquharson and McHugh have observed that the energy imparted to a vibrating conductor of given mean diameter is almost independent of the pattern of stranding or conductor roughness. Fig. (7.1) shows the curves for various types of models by which this conclusion is borne out. The average envelope of power curves is shown in fig. (7.2).

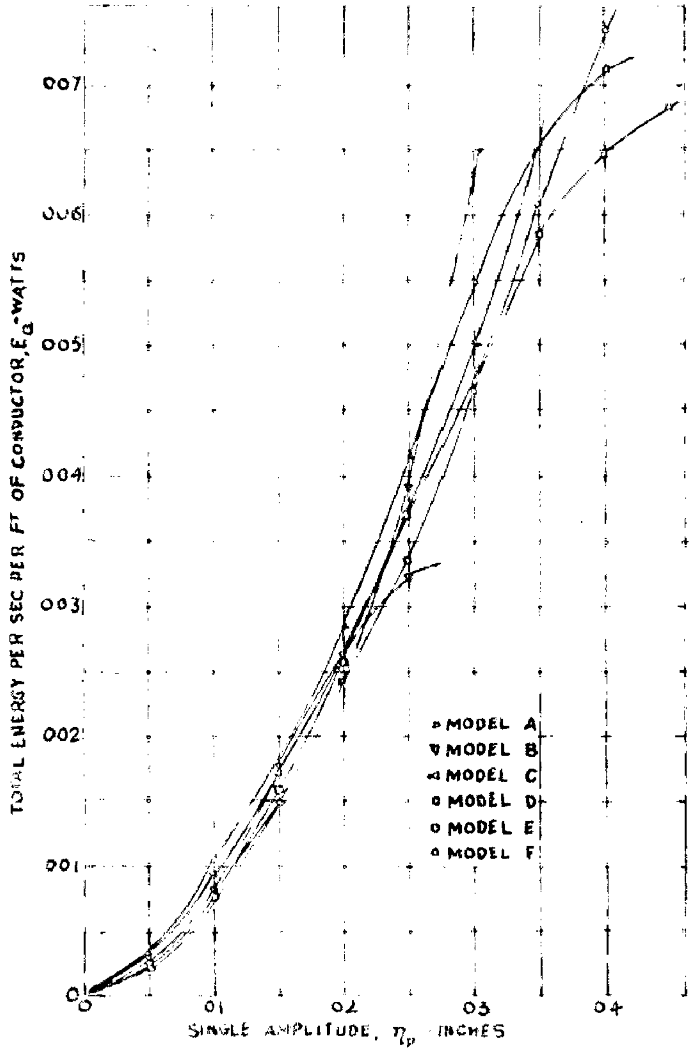


Fig. 7.1 - Energy imparted by wind - from model studies.

Model	A	6/1 A.C.S.R., strand diameter 0.75 inch.
Model	B	Expanded A.C.S.R. conductor, strand diameter 0.165.
Model	C	Expanded A.C.S.R. conductor, strand diameter 0.375.
Model	D	2.25 inch diameter smooth conductor.
Model	E	1.60 inch diameter smooth cylinder.
Model	F	4.00 inch diameter smooth cylinder.

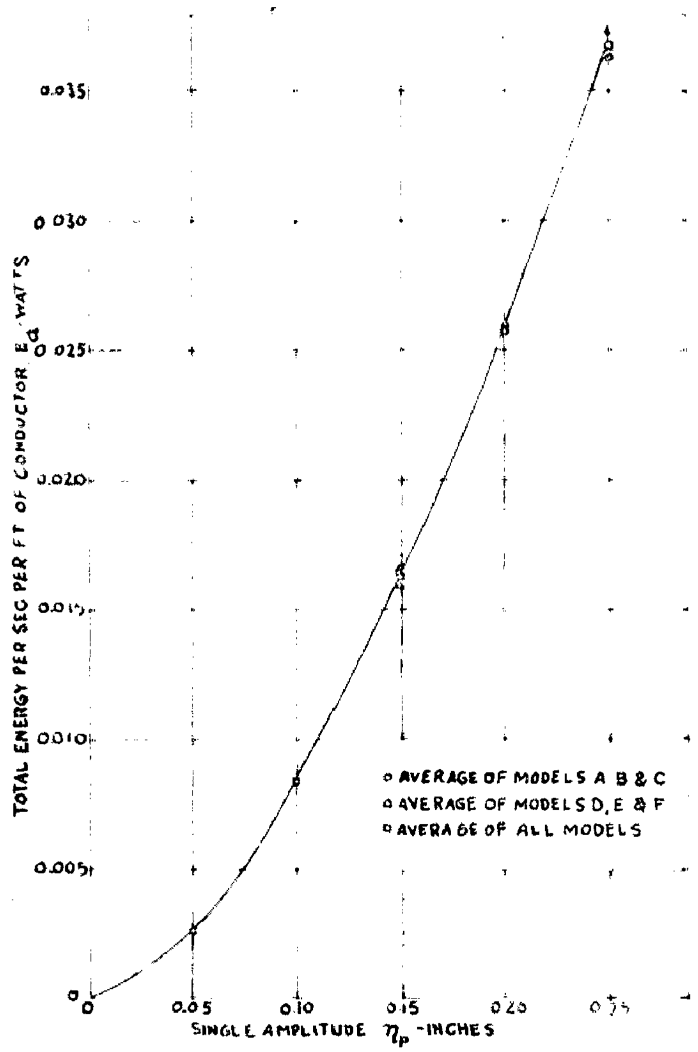


Fig. 7.2 - Average envelope of power.

(See subcaption of Fig. 7.1)

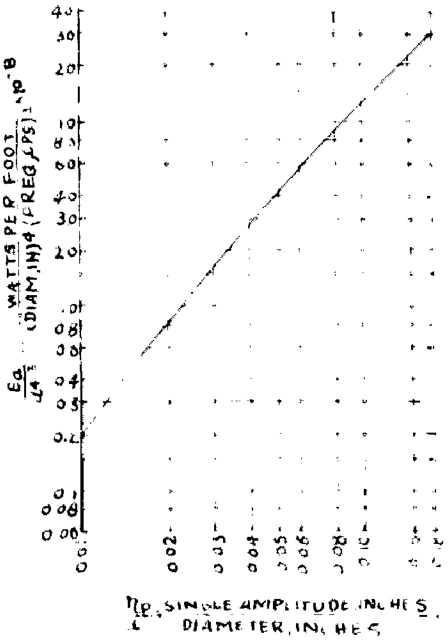


Fig. 7.3 - Predicted power from wind to a conductor vibrating in sine wave.

As a further generalisation the curve in fig. (7.3) is given. It is possible to read out from this curve the energy corresponding to any type of conductor if its diameter, frequency and amplitudes are known.

7.4 Energy dissipation(31)

This aspect has been explored by Rakowski(31). The relations which he has derived are given below.

Energy is dissipated internally in the conductors firstly as heat as the conductor is subjected to flexure because the molecules of the wire rub against themselves, and secondly due to friction between wire strands, wire attachments etc.

The total energy dissipated per cycle at an amplitude in still air has been shown as

$$E_T = \frac{D}{2} \cdot m \cdot \eta^2 \cdot \omega \cdot L \qquad \ldots \; 7.35$$

where D is a damping factor given by

$$D = \frac{2 \cdot \omega \cdot d}{\pi} \qquad \ldots \; 7.36$$

and d is the logarithmic decrement as defined earlier.

The expression derived for the aerodynamic energy dissipation attributable to the viscous flow of the atmosphere around the conductor is

$$E_A = \frac{32}{3\pi} \cdot 0.[illegible]\,\rho \cdot \omega^2 \cdot A^3 L \qquad \ldots \; 7.37$$

For damper matching the mathematical expressions are given in chapter 8.

CHAPTER - 8

VIBRATION DAMPING ARRANGEMENTS - OPTIMUM DESIGN

Under this broad general heading will be studied the efficient and optimum use of vibration suppressing as well as conductor protecting schemes as are in use. A reference will be made to their drawbacks and inadequacies regarding particular cases.

8.1 Classification

The methods of preventing fatigue failures in conductors due to vibration stresses developed, are in general of two types. The first is to protect the cable, against deleterious effects of vibration without trying to lessen it; the second is the damping of the vibration to the extent that it is not serious. Coming under the first category, are the methods of reducing the stiffness of fixation of the cable or its connection-thereby reducing the stresses of vibration; and the application of a protective covering to the region of high stress with the aim of having the protective covering carry most of the oscillating stress while the cable carries only the direct tension.

8.2 Flexible Supports

The schemes which reduce the stresses of fixation or connection consist of design of special clamps which have more flexibility and freedom of motion. A notable example, besides the normal string insulators (which has inherent

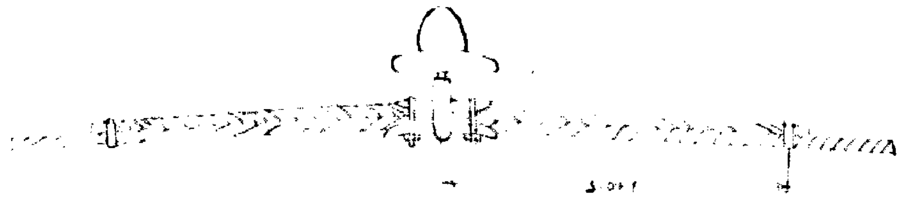


FIG 8.1(a) SIX FOOT CABLE ABSORBER.

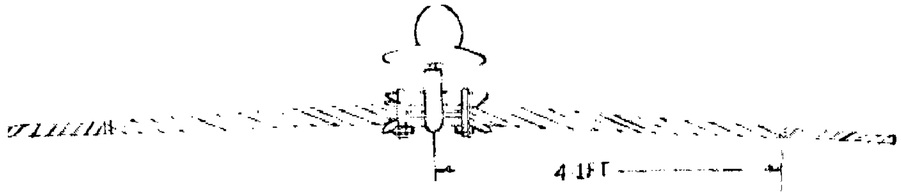


FIG 8.1(b) TAPERED ALUMINUM ARMOR RODS

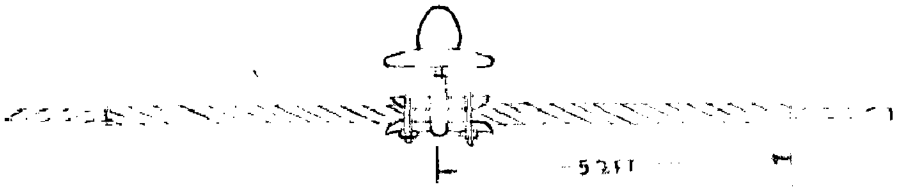


FIG 8.1(c) PREFORMED REINFORCING

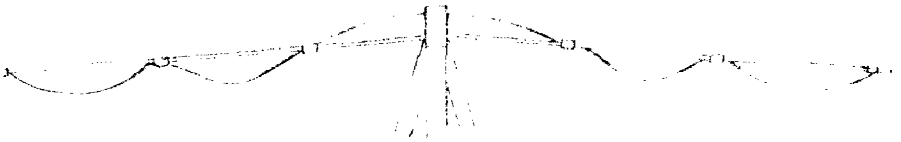


FIG 8.1(d) FESTOON.

flexibility), is a special type of strain insulator which has between the conductor and itself an oil dashpot which allows a relative motion and at the same time absorbs some energy in each cycle.

8.3 Coverings and Reinforcements

Protective covering at the point of stress concentration is provided in many forms. Chief among these are; the cable absorbers, tapered aluminium armour rods and preformed reinforcing at the supports.

8.3.1 Cable Absorbers

The cable absorber shown in fig 8.1a consists of a short piece of cable of the same material and size as the strung cable and clamped together with it at the support as well as a number of other points. The usual length of the cable absorber is about 3 feet on either side of the support. To avoid stress concentration due to clamps themselves usually aluminium is used as a material for the clamp.

8.3.2 Armour Rods

The tapered aluminium armour rod (See fig. 8.1b) has been in use for a number of years. Together with stockbridge dampers it was a satisfactory answer to the aeolian vibration problem in the early years when spans were shorter and line tensions small. As the name suggests it consists of a tubular tapered aluminium covering which is slipped on the conductor before clamping is done at the supports. It is very effective in the sense that it may reduce conductor stress by as mucha as 60 per cent.

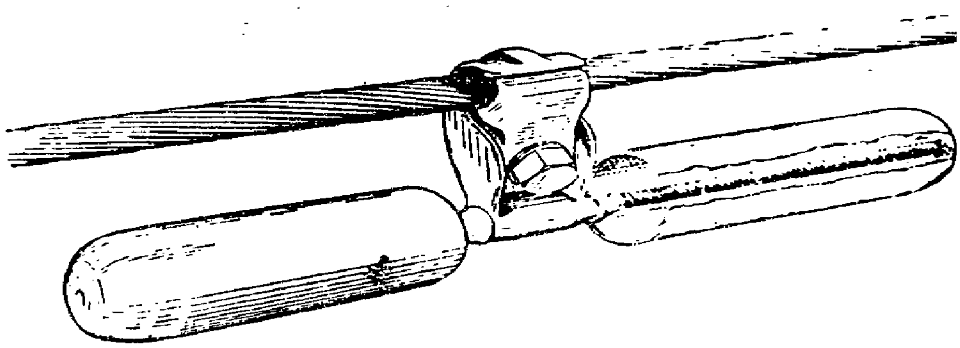


FIG. [redacted]. STOCKBRIDGE DAMPER

FIG. - 8.2
(Reproduced from ref. 18)

8.3.3 Preformed Reinforcement

The preformed reinforcing (fig. 8.1 c) is similar to armour rods except for its physical shape which is cylindrical instead of tapered. To be really useful both the armour rods and preformed reinforcing is provided for a length of more than 4 feet on either side of support.

8.4 Dampers

All these methods as explained earlier do not contribute anything to the damping and absorption of energy of the vibrating conductors except perhaps the case of the oil dash-pot strain insulator, and therefore they do not form by themselves a complete protection. Various kinds of damping schemes have been in use and the chief among these are the provision of either Stockbridge or torsional or the single degree of freedom sponge damper.

8.4.1 Stockbridge Damper

The Stockbridge damper (fig. 8.2) is perhaps the simplest and the commonest type. It consists of a piece of stranded steel cable which has weights attached to its ends. The centre of this steel cable is clamped on to the conductor. The cable acts as a spring and is roughly tuned to the frequency of the expected vibration. Any motion of the line at the clamping point will cause relative motion between the various strands and the friction thus produced dissipates energy. The point of attachment is so chosen along the line that it can not coincide with a node of the motion

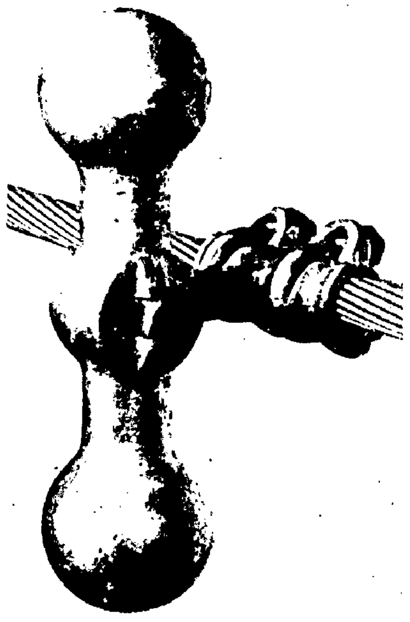


Figure [illegible]. Torsional damper for 795,000-circular-mil ACSR

FIG. - 8.3
(Reproduced from ref. 11)

where the damper would be useless. This rules out its installation at the point of support. A detailed explanation of the choice of damper and its spacing from the supporting structure will be found in chapter 9. The damper in its original form was a crude device. It has undergone many refinements since 1925 where it was first suggested. Together with in-span damping methods and stabilizing weights it has been found to combat aeolian vibration fairly well.

8.4.2 Torsional damper

The torsional damper (Fig. 8.3) was devised by the Hydro Electric Power Commission of Ontario for similar purpose in 1941(11) and in a way is more efficient. It consists of a dumb bell type eccentric weight clamped to the conductor with a resilient arm (to avoid stress concentration due to clamping as well as the action of the weight). It acts on the principle of conversion of translational motion to rotational motion. It is well known that when a vertical motion is imparted to an undamped span the resulting travelling wave may be clearly identified after several cycles of travel between the towers. When a torsional motion is imparted to the same span the resulting torsional wave' gets attenuated much rapidly. A converter to transform the wind imparted vertical oscillations to the highly damped torsional wave is in its simplest form a mass clamped to the conductor with its centre of gravity horizontally displaced from the centre of the conductor which is what a torsional damper basically is.

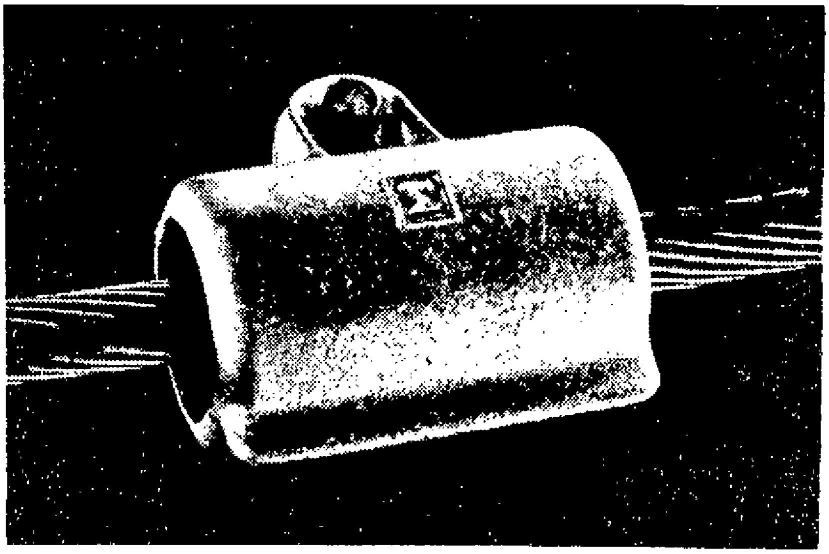


Fig. [illegible]. Sponge damper on Drake conductor, 1.1-inch diameter. Damper is constructed with neoprene sponge confined in a cast-iron casing, 6 inches long

FIG. - 8.4
(Reproduced from ref. 30)

The coupling in this case between the translational and torsional motion is of the 'inertial' type.

[illegible] 'Single degree of freedom' damper

The single degree of freedom damper (fig. 8.4) is perhaps the latest type of damper. It was suggested in [illegible](30). However its efficiency has been fairly well established by extensive laboratory and field tests as well as accelerated aging tests. It operates on the principle of confining the conductor over an appreciable length with a filler material in such a way that it resists conductor motion. It consists of a cylindrical metal casing with an inside diameter about 8 times the external diameter of the conductor. The casing is in two halves and can be put on the conductor with a nut and bolt. The space between the conductor and the casing is filled with a spongy material such as neoprene or silicon neoprene. This constitutes a mechanical system with a single degree of freedom and its resonance frequency depends on the stiffness of the filler material and the weight of the casing which are so selected that the resonant frequency is below the prevailing Strouhal frequencies of the conductor. Due to mass inertia of the damper casing it remains almost steady and motionless in space and the motion of the conductor compresses the filler material which because of its stiffness provides a resisting force and in the process absorbs the vibration energy.

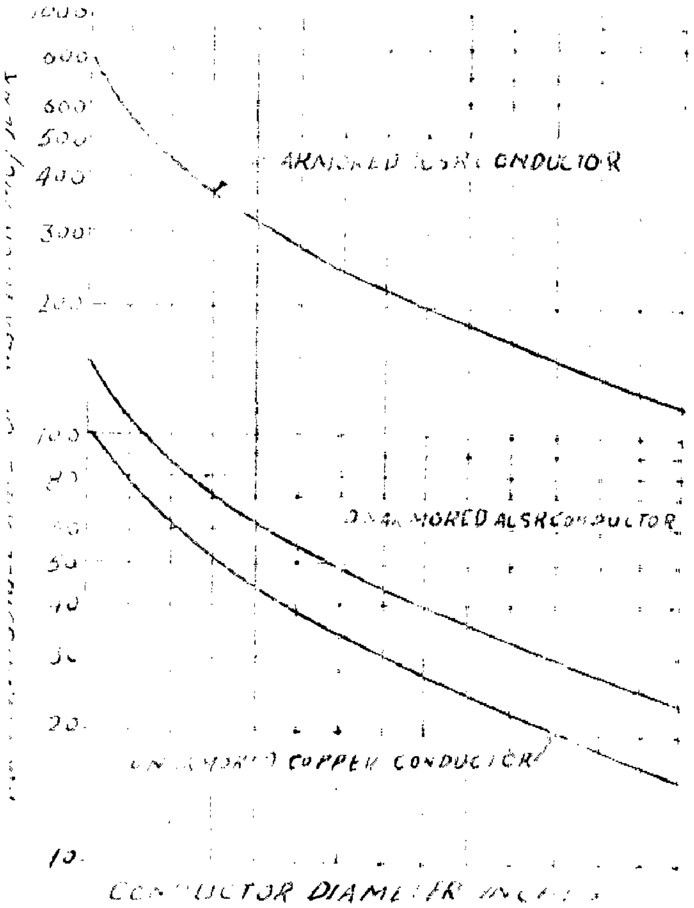


FIG 8.5 VIBRATION PROTECTION CRITERION

[illegible] RATE ABOVE WHICH DAMPER INSTALLATION IS JUSTIFIED

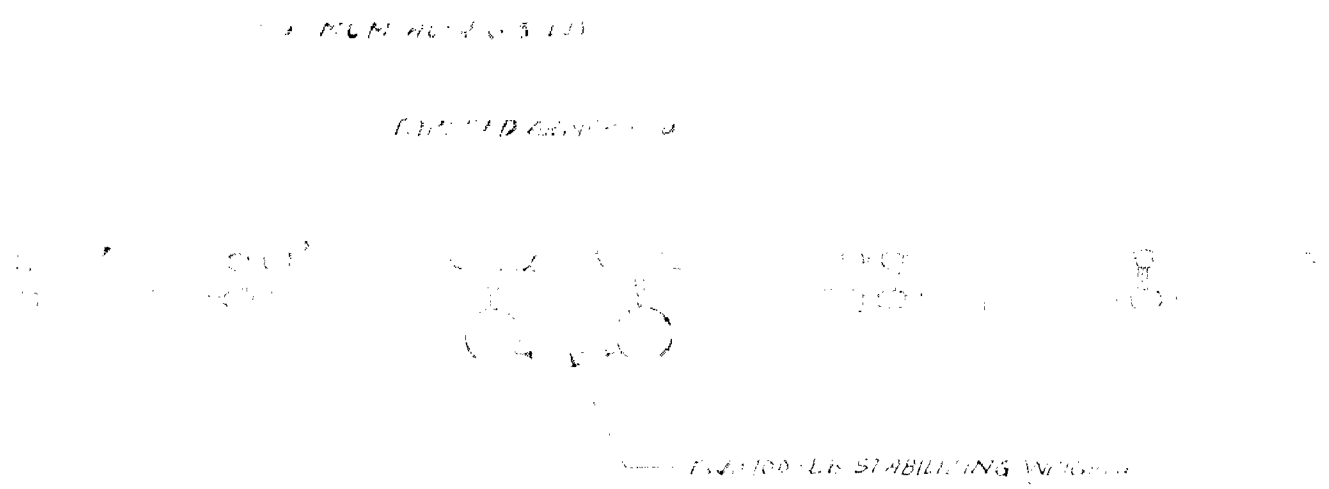


FIG 8.6 IN SPAN DAMPING METHOD

8.5 Optimum Damping

According to the conventional practice each conductor span is provided with two dampers attached at either ends. On ordinary spans (the spans in which tensions are kept between 10 - 20 per cent and have lengths upto 1800 feet), where the tendency for severe vibrations is less pronounced this has been observed to provide more than adequate damping$^{(23)}$ and in fact some economy could be effected by reducing their number. Some investigators are of the opinion that unarmoured ACSR conductor may withstand an indefinitely large number of stress reversals if the operating tension at 60 degrees F is less than 20 per cent of the ultimate strength of the conductor. There has been developed a definite vibration protection criterion from service experience$^{(24)}$ which can be useful in selection of spans on which dampers should be installed (fig. 8.6). It consists of a set of curves for the various types of conductor (stranded, armoured, unarmoured) drawn between the diameter of the conductors and the maximum permissible rate of vibration of the conductor in megacycles per year, above which the installation of suppressing schemes is indicated. This rate of vibration for each span or the representative spans can be measured by the Jacquet cycle counter discussed in chapter 4 Sec. 3.2. It is a cheap and light instrument, weighs about 10 ounces and can be clamped to the spans by using the normal hot line tools, without disturbing the continuity of supply.

Protection provided on the basis of this criterion is called as SELECTIVE PROTECTION. However this criterion does not give any idea as to the number of dampers that need be installed on individual spans. To prevent conductor failure, it is necessary only to provide sufficient vibration control to reduce the stresses to a level below that which causes fatigue failures of the conductor. With the torsional dumb bell type dampers if not the Stockbridge type economy and optimisation could perhaps be effected on ordinary spans (as explained earlier) by providing only one damper per span without jeopardising safety. This has been tested and verified o many spans in Canada and the results of those tests bear testimony to the conclusion, and is therefore well worth keeping in mind when designing transmission lines with the aim of reducing capital cost.

The above discussion does not hold for the spans of extra ordinary length and tension as also those situated in places of adverse weather conditions. It is in fact in those cases that vibration is a major problem for reasons discussed earlier and there fore each of them has to be attended individually and its protection scheme worked out.

8.6 IN-SPAN Damping

The problem of aeolian vibrations of long river crossings has been solved to a great extent by what is called as the method of in-span damping as recommended by the Aluminium Company of America. The approach is based on the principle of shortening not the actual span but the effective span length and consists of installing stabilising weights at one or several points in the long span and to apply normal damping arrangements adjacent to these weights as though they were towers. (Fig.8,6). Proper or predicable operation of dampers requires their installation near a point of wave reflection so that their location with respect to nodes can be predetermined. Support points usually comply with this requirements. But heavy stabilizing weights can also do it. In this case therefore the effective span length becomes the distance between adjacent stabilizing weights or a distance between a tower and the nearest stabilizing weights. The dissipative load on each damper is thus reduced several fold. It has been observed that damping can be effective if two dampers are spaced properly with each other far out in the sapn without stabilizing weights. However placing a single damper far out in the span has almost no damping effect.

In evidence of the above condlusions the ALCOA has given the following gist of its observation on test site (a typical long river crossing)

	Conventional damping	In-span damping	Remarks
1. Persistence of the vibration (ground wire)	34 per cent of the time	6 per cent of the time	A reduction of 82 per cent
2. Persistence of the vibration-conductors	14 per cent of the time	2 per cent of the time	A reduction of 86 per cent
3. Amplitude (ground wire and conductors).	100 percent (reference)	60 percent	Total reduction in severity of vibratien, 93 p.c. for ground wire and conductors.

In the above table the product of duration and amplitude is used ~~w~~as an index for the severity of vibrations.

8.7 Suppression of Galloping

The installation of damping devices is a practical proposition for mitigating the effects of aeolian vibration only. From the above discussion it is clear that this aspect of the general vibration problem is fairly completely tackled. Unfortunately, same can not be said about galloping. None of the above damping schemes would dissipate even an appreciable fraction of the vibration energy and in fact to dissipate the energy corresponding to amplitudes of 20 feet peak to peak at 1 c.p.s., Stockbridge or other dampers would have to weigh several tons which is evidently entirely impractical to use.

Because the mechanism of excitation of the two phenomena is different the approach to the alleviation of the problems is also different. Aeolian vibration is unavoidable because it does not depend on the geometric cross section of the conductor. And because this problem can not be solved at the 'cause' end it is tackled at the 'effect' end. However in this matter the galloping phenomenon differs. Because it depends on the geometrical profile of the conductor there is one factor on which control can be exercised. That is in other words this problem can be tackled at the 'cause' end. Instead of letting vibrations build up and then trying to damp them effort could be made in this case to reduce or eliminate the excitation to the vibration itself. Yet the problem is not as simple as it might look. Although making of the profile of the conductor aerodynamically stable is the straight forward solution there are many difficulties in doing it. Under non icing conditions the cross section of the conductors except in cases of stranded conductors is aerodynamically quite stable (circular conductor profile) and tendency to gallop does not manifest itself. Stranded conductors even under non icing conditions may show instability in many cases and the remedy which has been suggested for them is to even up their circumference to make them as nearly circular as possible. This can be done in two ways. One is to coat the conductor with some kind of grease or lubricant to fill up the recesses andvoids. The other is to wrap an adhesive p.v.c. tape round the conductor and make it circular. The latter remedy although a rather recent one has to be found to be quite effective, the former suffers from the drawback that it fails to produce permanent result and regreasing on strung conductors is not possible.

With a simple machine specially built discussed in reference 34, taping of the conductor on the strung spans is possible. The equipment is not live line type but conductors do not have to be taken out from the lines for this purpose, which causes the discontinuity of supply for a relatively short time.

For the galloping of the conductors due to ice and sleet formation on them and consequent instability, an acceptable solution does not exist. One method that has been suggested is to increase the I^2R loss in the conductor by increasing the resistance so that it may be sufficient to melt the ice formed but this is not an acceptable solution because considering the large amount of heat required to melt the ice it is wasteful of electricity. The prospect of this drain on energy becoming a permanent feature of the transmission system is not very aggreable.

It is in fact this aspect of the galloping which has baffled the investigators so far and which requires an urgent solution.

CHAPTER - 9

MECHANICAL IMPEDANCE - MATCHING OF DAMPER CHARACTERISTICS - ELECTROMECHANICAL ANALOGIES

9.1 Similarity between a Vibrating Conductor and long Electric Transmission Line with Distributed Constants

The differential equations for a vibrating conductor with negligible stiffness

$$\frac{\partial^2 F}{\partial z^2} = \epsilon \cdot \frac{1}{T} \cdot \frac{\partial^2 F}{\partial t^2} + R_m \cdot \frac{1}{T} \cdot \frac{\partial F}{\partial t} \text{ ------- } (9.1)$$

$$\frac{\partial^2 v}{\partial z^2} = \epsilon \cdot \frac{1}{T} \cdot \frac{\partial^2 v}{\partial t^2} + 6\, R_m \cdot \frac{1}{T} \cdot \frac{\partial v}{\partial t} \text{ ------- } (9.2)$$

The differential equations for an electric transmission line with destributed constants is

$$\frac{\partial^2 V}{d_z 2} = L.\ C.\ \frac{\partial^2 V}{\partial t^2} + (RC + LG)\ \frac{\partial V}{\partial t} + R.G.V. \text{ ----- } (9.3)$$

$$\frac{\partial^2 I}{\partial z^2} = L.\ C.\ \frac{\partial^2 I}{\partial t^2} + (RC + LG)\ \frac{\partial I}{\partial t} + R.G.I. \text{ ----- } (9.4)$$

where F is the force normal to the axis of the conductor at any point, ϵ the mass per unit length, T the tension, R_m the mechanical resistance i.e. the resisting force per unit length per unit velocity, v the velocity of the conductor normal to its axis at any point in equations 9.1, 9.2 and V is the instantaneous voltage on the transmission line at any point, I the current in the conductor at any time, L, C, R and G the distributed constants in equation 9.3 and 9.4.

Z is the distance of the point considered from the origin along the conductor.

If in equations 9.3 and 9.4 the conductance to ground G is considered as zero, then the equations become

$$\frac{\partial^2 V}{\partial z^2} = L.\ C.\ \frac{\partial^2 V}{\partial t^2} + R.\ C.\ \frac{\partial V}{\partial t} \qquad --- \quad (9.5)$$

and

$$\frac{\partial^2 I}{\partial z^2} = L.\ C.\ \frac{\partial^2 I}{\partial t^2} + R.\ C.\ \frac{\partial I}{\partial t} \qquad --- \quad (9.6)$$

which are the same in order and pattern to equations 9.1 and 9.2 which hold for the mechanical vibration. However this similarity ceases if the conductor stiffness in 9.1 and 9.2 and conductance to ground in 9.3 and 9.4 is considered. However neglecting these quantities is not an irrational assumptions and experience of people actively engaged in vibration research has corroborated the argument that for the purpose of analysis these may not be taken into account for most of the practical purposes.

Thus there is a clear analogy between the two phenomena and this has been found to be very useful because the conductor vibration with it can be studied critically through its simulated electrical network.

9.2 Analogous Quantities

The quantities that are analogous to each other in these two physical phenomena are

Electrical		**Mechanical**	
Voltage :	V	Force :	F
Current :	I	Velocity :	v
Resistance :	R	Mechanical resistance :	R_m
Inductance :	L	Mass per unit length :	ϵ
Capacitance :	C	Reciprocal of tension :	$\frac{1}{T}$

9.3 Use of the Analogy

The techniques for handling electrical transmission lines are quite well developed and with this analogy they can all be applied to the theory of conductor vibration. Solutions thus obtained of course do not take into account the stiffness of vibrating conductor and are to an extent approximate, but they are very useful nontheless and errors introduced are rather insignificant except perhaps at higher frequencies. However methods have been developed which partially compensate for these errors.

For convenience of this analogy we assume that the energy input from the wind to the conductor is imparted at the centre of the span. The span can then be considered as two separate half spans with half the total energy input going into each half span which then can be considered as being driven by a harmonic force at one end and terminated at a fixed point at the other. The half span is analogous to an open circuited electrical line with an alternating voltage applied at the generator end. This is true because the fixed point at the end is at zero velocity which must correspond to zero current or open circuit.

Application of dampers near the end of the span can be considered equivalent to insertion of a 'lumped' impedance in series with the transmission line at a corresponding point, if we assume that conductor clamp has zero length that is its action is not on a distributed part of the length of the span and also if we assume that the dampers can act only as a force

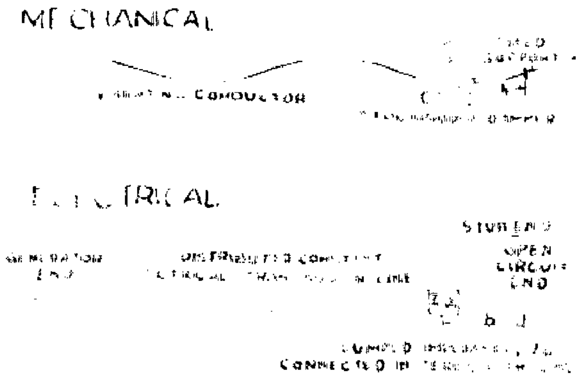


Fig. [illegible] — [illegible]
[illegible]

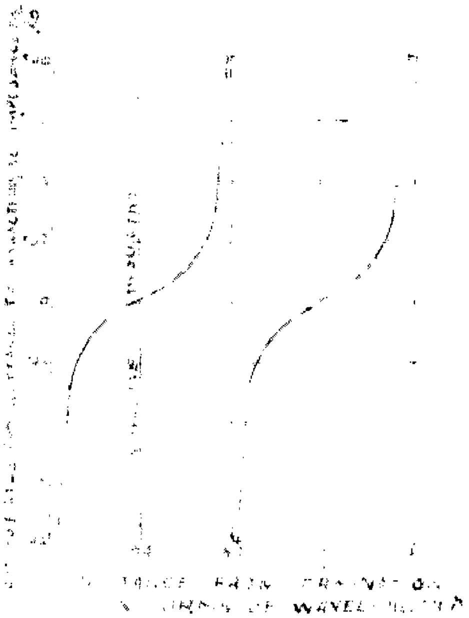


Fig. [illegible] — [illegible] end reactance of [illegible] line at right angles to 'at-rest' position of the conductor.

Shown in Fig.9·1 is an analogy of the damper mounted on the conductor, power ~~mp~~ input being assumed concentrated at the centre of the span. The analogy dictates the inclusion of series impedance to correspond to the given damper installation because the velocity of the damper clamp will be same as that of the point on the conductor to which it is connected and same velocity would mean same current in the simulated network.

9.4 Matched Dampers

The most effective damper for any given frequency that can be installed near the end of the span would be one which is able to absorb maximum possible power from the conductor at that frequency. This will make the power dissipation maximum, and the conductor vibration a minimum.

The mechanical problem of specifying the characteristics of such a damper is similar to the electrical problem of specifying the characteristics of a lumped impedance inserted near the end of a long line so as to provide for the maximum transfer of power from line to the terminating impedance.

From the application of maximum power transfer theorem to long transmission lines we know that the power transfer to the terminating impedance is maximum if its value is equal to the conjugate of the characteristic impedance of the line.

The characteristic impedance Z_o is

$$= \frac{R + j W L}{G + j W C} = R_o + j X_o$$

where Ro is the resistive component and Xo is the reactive component of Zo

Zo for a loss less line is equal to $\sqrt{\frac{L}{C}}$

From analogy has been developed the concept of mechanical impedance which is the ratio of excitation function (force) to the response function (velocity) in the case of any mechanical vibrations; just as electrical impedance is the ratio of voltage function to the response or current function.

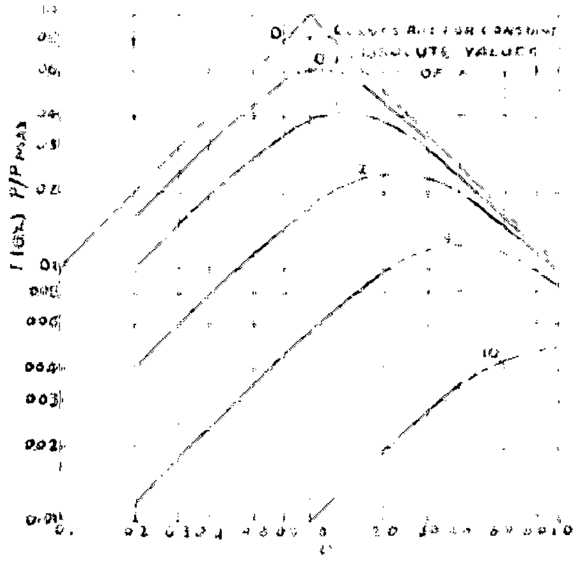
In the case of conductor vibrations therefore, on the pattern of long transmission lines we define what is called as the characteristic mechanical impedance (Z_m). This quantity for the assumed half span is equal to

$Z_m = \sqrt{T.E} = \sqrt{\frac{T.W}{g}}$ where W is the weight of the conductor per unit length.

For an idealized conductor the maximum possible damping would be provided if the termination of the span presented a mechanical impedance equal to the conjugate of the characteristic impedance, or, since the imaginary part is absent in the characteristics impedance, simply equal to the characteristic mechanical impedance.

If a lumped impedance Z_a is connected into an electrical transmission line at a distance h from the open circuited sapn, the impedance of the 'stub end', the portion between the location of the lumped impedance Z_a and the open end of the line as viewed from the location of Z_a is

$Z_s = Z_0 \coth \gamma h$



ig. 9.[illegible] [illegible] idealized line

δ = ratio of effective [illegible] termination to characteristic resistance of line.

= ratio of [illegible] of terminations to characteristic resistance of line,

P/P_{max} = ratio of power [illegible] to maximum possible power which can be transferred to the terminal[illegible] where Z_s is the impedance of the stub end.

$$\gamma = \alpha + j\beta \quad \sqrt{(R+j\omega L)(G+j\omega C)}$$

For an ideal line with R and G both zero Z_0 equals R_0 and stub end impedance becomes a pure reactance as γ or $j\beta$ becomes equal to $j\omega\sqrt{L.C}$

$$Z_s = R_0 \coth(j\omega\sqrt{LC}\;.\;h) = -jR_0 \coth(\omega\sqrt{LC}\;.\;h) = jR_0 \coth \beta h$$

$$\beta = \omega\sqrt{LC} = \omega.1/v = 2\pi.f/f.\lambda = 2\pi/\lambda$$

v = velocity of propagation and   is the wavelength.

As viewed from the generator end the line appears to be terminated in an impedance Z_0

$$Z_0 = Z_a + Z_0 \coth \gamma h$$

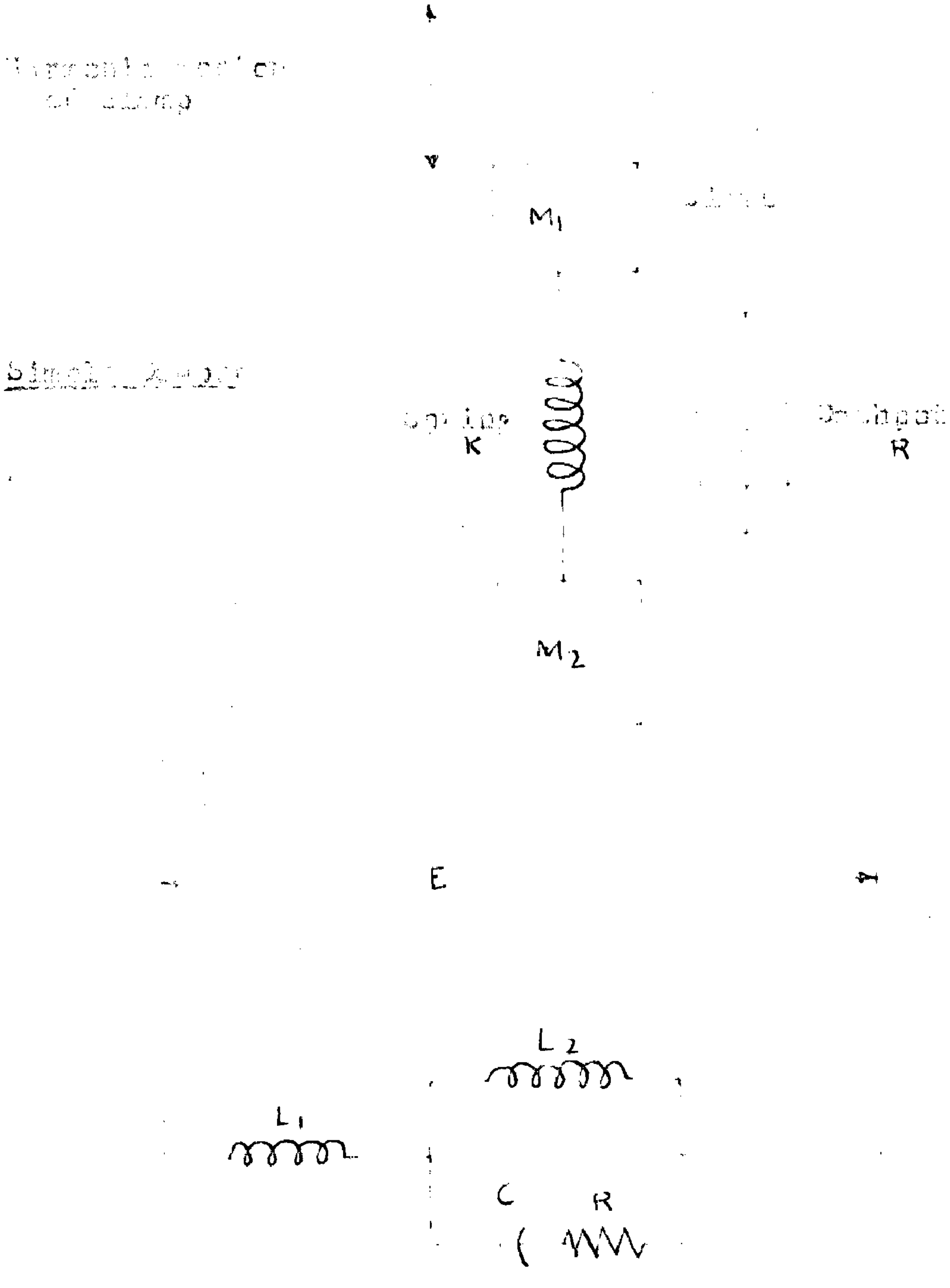
or in the ideal case

$$Z_0 = Z_a - jR_0 \coth \beta.h$$

Fig.9.2 illustrates the variation of the stub end reactance with the distance . If h is an odd number of quarter wavelength the reactance of the stub end is zero. In this case for maximum power transfer Z_a should be a pure resistance equal in magnitude but opposite in sign to the reactance of the stub end and the resistance component of Z_a should be equal to R_0.

For the idealised mechanical problem, for maximum possible damping the damper should be designed to have a mechanical impedance with the resistance component equal to the characteristic impedance of the vibrating conductor, and reactance component equal but opposite in sign to the reactance of the stub end which in idealised case would be

$$Z_s = -jZ_0 \coth \omega\sqrt{\frac{m}{T}}$$



Electrical ~~analysis~~
analogy

Fig. [illegible] - Schematic representation of simple damper and its electrical analogy.

9.5 Multiple resonant frequencies

So far, the problem of matching the damper characteristics with those of the line appears to be fairly easy. However the problem is quite complex because of the fact that the vibrating span does not have a single resonant frequency and therefore the exciting force function has multiple frequencies. A solution found to be optimum for one frequency, may prove out to be entirely inadequate for the other harmonic frequencies. To meet the requirements of these conditions, we have to develop the relationships for the ranges of frequencies present and then select and apply practical dampers for optimum damping over these frequency ranges and then determine their effectiveness.

If the terminating impdeance has not been matched with the line properly, we know that it gives rise to standing waves because of reflection from the receiving end. The power transfered to termination is this case can be shown to be equal to

$$P = (I_{max})^2 . R_o . F(\theta, \chi)$$

where I_{max} is the magnitude of the current at current maxima. θ is the ratio of the effective resistance of the termination to the characteristic resistance of the line and χ is the ratio of the effective reactance of the termination to the characteristic reactance of the line. If the losses in the line are negligible (i.e. G. is zero) then F (θ, χ) can be shown to be equal to

contd.

$$\frac{2\,\theta}{(1+\theta^2+\chi^2) + \sqrt{(\theta^2+\chi^2-1)^2 + 4\chi^2}}$$

(See page 892 of Reference 18)

With the line properly terminated the maximum amount of power is transfered to the termination and this is very closely

$P_{max}{}^2 = I_{max}{}^2 \,.\, Z_o$

In ideal line without losses

$P_{max} = I_{max}{}^2 \,.\, R_o$

and then

$P = I_{max}{}^2\, R_o\, F.(\theta,\chi) = P_{max}\, F\,(\theta,\chi)$

$F\,(\theta,\ ) = P/P_{max}$ -------------

The values of $F\,(\theta,\ )$ are shown in Fig.9.3 for various values of θ and . It can be seen from these that the changes of resistance have a lesser effect on $F\,(\theta,\chi)$, the fraction of total maximum power transferable that is actually transferred, than the corresponding change in terminating reactance. This can be construed in the mechanical system as to mean that the reactance of the damper and its spacing from the supporting structure is more important.

9.6 Damper Matching for a Range of Resonant Frequencies

Coming back to the selection and placing of the dampers on the transmission line conductors so as to cover the entire range of wind velocities. Obtaining in the terrain in question it can be said that with the insight provided by the work done so far in the vibration research and analysis, it has been made possible to find a fairly acceptable solution to this problem.

The inherent power dissipation in the conductors due to interstrand friction and other causes is proportional approximately to the sixth power of the frequency, while the power input from the wind to it for a given amplitude varies as about the third power of the frequency or the wind velocity. At low frequencies the power dissipated in the conductor is small but at higher frequency it increases at a much greater rate than the power input from the wind and therefore the power dissipation required in the conductor initially increases with the increasing frequency then reaches a maximum and then decreases due to self damping abilities of the conductor. For the usual damper applications, if f_{max} is the frequency corresponding to the maximum velocity at which vibration could be expected in the absence of dampers, it is found that the maximum power dissipation in the dampers is required at approximately 0.4 f_{max} to 0.75 f_{max}, depending on the amplitude of interest. If the damper is located so that it would be one half of a loop length from the span ($\lambda/4$) at 0.5 f_{max} the reactance of the stub end position of the conductor would be zero at 0.5 f_{max}. Similarly the mechanical reactance of the damper passes through zero at its natural frequency. The net mechanical reactance would be small if damper is selected whose upper natural frequency is about 0.5 f_{max}.and is located a quarter wavelength away from the span at 0.5 f_{max}.

The mechanical resistance of the damper would be expected to be equal to the characteristic resistance of the line. However to ~~the~~ improve the effectiveness over the entire frequency range the mechanical resistance has to be kept several times the characteristic resistance. This requires the study of the line on the analog model and choice of a suitable value which is satisfactory in each particular case.

CHAPTER - 10

COMPUTER APPROACH

Vibration studies of simple mechanical systems are usually done by methods which, though not difficult, often require the expenditure of enormous amount of time when done by hand. The use of computers both digital and analog type, shorters the time considerably. As will be noticed in the chapter on quantitative relationships, the algebraic expressions for stresses and strains are quite cumbersome. Digital computer studies would allow a very much more precise computation, and at the same time enable the solutions to be worked out f~~o~~r a large number of working conditions and thus prove to be of enormous help in the design of supporting hardware.

Analog computer studies could be useful for these as well as for the damper analysis for which ready made differential equations are available. It needs to be stated here that the study of the effects on damper impedance minute changes in the design parameters, on analog computers, is perhaps the best approach to damper matching. This is all the more so because the analog computers are capable of dealing with the non-linear driving functions and discontinuities which other wise require simplifying assumptions which affect the validity of the results. The particular solutions of the differential equations give the steady state performance and the complimentary solution gives the transient performance.

In the more straight forward differential equations for the aerodynamic instability coming under galloping the digital computers have been used for root solving as well as for the other and there is a tremendous amount of them - arithmetic al calculations. The equations arrived at after consideration of all the minor and major forces on the conductor as in ref. 29, are so involved and the final criterion contains the elements of such inwieldy determinants, that computer approach remains the only solution. The digital computer with the use of matrix solution methods has already been put to such use and has enabled valuable information to be obtained.

CHAPTER - 11

STUDY UNDER INDIAN CONDITIONS

No detailed study of aeolian vibration or galloping on power conductors has so far been done in India and therefore mostly the protection schemes used are exactly those which were in vogue in the western countries a decade ago. In fact the only dampers seen on Indian transmission lines are the Stockbridge type because the importance and utility of other types of dampers has not been fully appreciated. Conductor reinforcement at supports is done by tapered aluminium armour rods only-but that is quite adequate. In-span damping and optimum damping techniques are not employed and all spans long or short carry same standard pattern of two Stockbridge dampers per span which might be uneconomic for one span and inadequate for the other. On long river crossings conductor failures as well as tower failures have been reported but nothing is done beyond just repairing them.

Aeolian vibration and galloping under non icing conditions are perhaps much more important in general from the point of view of Indian transmission systems than the galloping under icing conditions because of the hot climate. However in the northern most part of the country, ice and sleet does form on the conductors during winter after snow fall. At present there is no important transmission system in that region but chances are that the huge potential power resources of the Himalayan region will soon be harnessed in stages to make up for the power shortage in the rest of the country and then long transmission lines will be laid in the design of which one of the first and foremost considerations would be to reduce their vulnerability to galloping after snowfall. At present however this trouble confines itself to the telephone wires and the distribution conductors mainly in the coldest parts of northern India. As discussed in chapter 8 the solution to galloping under icing conditions does not exist. It would be in the interest of the Indian power supply companies to keep themselves abreast of the new development in this side of the problem as a lot of active research work is going in other countries where the problem is very much more acute. However the study of the other two sides namely the aeolian vibrations and nonicing galloping is rather more justified & long overdue in India.

Firstly the schemes of in-span damping and use of torsional dampers as well as the signle degree of freedom dampers will have to be given their due place but at the same time all these things can not be used blindly as they are used elsewhere. The vibration protection criterion would have to be modified for these schemes so as to suit the particular types of conductors and supporting structures as well as the prevalent strouhal frequencies (which depend on the wind velocity besides the conductor diameter). Also the spacing of dampers should no longer be done on the basis of set formulae but consideration must be given to mechanical impedance matching (chapter 9) so that a more efficient use could be made of the sizes and their characteristics can not be changed. For representative spans and for extra ordinary spans the analog model studies are to be recommended as with them the conductor performance would be easily predicted, difficulties foreseen and alternative arrangements worked out.

The galloping under nonicing conditions has also to be studied in detail to reduce span vulnerability. For the present the taping of the conductors with an adhesive p.v.c. tape is the best solution and this must at least be done on long river crossings. Where due to its large length and tension the conductor shows the maximum tendency to gallop. Stranded conductors should in these cases be taped before installation as far as possible otherwise this operation would have to be done on site under strung conditions which is rather inconvenient (but is possible) circular conductors need not have any such treatment given to them.

CHAPTER - 12

CONCLUSION

The discussion in the preceding pages indicates that vibration problem of transmission lines is by no means as innocuous as it appears at first sight. The vibration considerations if not fully appreciated at the design level result often in substantially high costs of repairs and replacements due to the vulnerability and susceptibility of the line to the damages described. A number of preventing and remedial measures that are now economically feasible deserve to be made best use of. These are for reasons already discussed, certainly not a completely satisfactory solution, the complexity of the problem being almost unlimited. Even the aeolian vibration which is claimed to have been tackled completely is troublesome at particular frequencies with the tuned dampers. It is true that this problem is more amenable to solution than its counterpart that is galloping.

Inspite of the commendable amount of work done on galloping its solution has been possible only under specific conditions namely the non-icing ones. Investigations are still going on and it can be hoped that in near future specific methods for reducing the conductor instability under all types of conditions would be available.

The analysis of aeolian vibrations is more or less satisfactory although one wishes that more regorous information were available about the energy inputs and dissipations.

At present this is in a quasi-mathematical stage. The stress strain analysis leaves little to be desired. The fields in which further research is going on and whose results promise to be useful are mainly the improvements of damping schemes developments of more rigorous criterion for indicating the need for vibration protection, determination of conditions under which armour rods and dampers are both required and when either is alone sufficient.

The accurate prediction of vibration life of conductors already in service is also an aspect to which a categorical answer is required. Design of supporting clamps and accessories has by no means reached a stage of perfection further research and modifications are necessary.

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