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Predominant Factors Involved in Cable Vibration

An attemt to summarize present knowledge on vibration

by

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This report is based
on CSC 6-62-21 and 22

CONTENTS

1. Preface.

1. In this paper I want to consider every parameter which, in my opinion, plays a more or less dominant role in the problem of vibration. Further, I am trying to clarify the way the different factors enter into this complexity, and the importance of each factor. In other words, I want to state the quantitative relationships between factors involved in cable vibration.

2. In an attempt to give as complete an account as possible, it has been necessary to include a number of points which might appear obvious.

3. Some subjects are dealt with in greater detail than others. One subject is studied in particular detail in an annexe to the report, viz. that entitled "Rigidity and Internal Damping of Tensed Stranded Cables", originally document CSC 6-62-22.

4. The question of additional damping - extra damping devices - has not been dealt with in this report. this question beeing studied by a special working group within CSC 6. However, conclusions arrived at in this group should logically be incorporated as part of a final report summarizing all available knowledge on cable vibration. Moreover, knowledge on the theory behind the dancing and galloping cables and oscillation of bundle conductors should be summarized in the same way to give a complete picture of oscillation phenomena of transmission lines. "Corona Vibration" should also be dealt with.

5. I would not claim that this report includes all significant views: Its contents are based on the experiences of myself and others, and on acquaintance of the material, acquired either in operational and maintenance work, in the design of transmission line fittings and dampers, as well as on theoretical and experimental studies of certain aspects of vibration e.g. the salient features of suspension clamp and fixing device design, the significance of cable rigidity as well as investigations into the vibrations in fjord spans, and more especially in extensive

reading of litterature on this subject and talks with acknowledged experts. Only a fraction of the comprehensive body of litterature perused has been included in the bibliography appended to the report. Thus the viewpoints and conclusions set forth may be said to represent a synthesis of the sum of knowledge available to myself on this subject, which I have endeavoured to present in as practical manner as possible.

6. My report was intended to be a draft, and my object was to provide a basis and preamble for a discussion which I think should be initiated amongst selected vibration experts. Through the work of CSC 6 I had hoped to obtain a critical appraisal of its contents, as well as of the various conclusions arrived at. Furthermore I had in view that, as the work of CIGRÉ in this field progressed it might be possible to keep the report up-to-date at all times, as new information and knowledge become available, in the light of fresh experience and investigations, both experimental and theoretical.

Mr. T.O. Slethei of The Norwegian Research Institute of Electricity Supply has been helping me with the revision of the report.

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2. Introduction.

7. It has been found useful to divide the problem into two parts, adopting the two terms Vibration Intensity and Endurance Capability. These terms are of a specific nature for each span. The first term Vibration Intensity, indicates to what extent the span tends to vibrate. This term also includes the influence excercised by the environments of the span, e.g. topography, vegetation, etc. Before supplementary damping devices have been added, the term used should be Natural Vibration Intensity. The vibration intensity is characterized by the amplitude, frequency and duration of the oscillations. The second term, Endurance capability, indicates how the different components of the span, e.g. the cable, the fixing devices, towers etc. withstand the additional strains induced by the vibrations.

8. The aim should be to mention all factors which influence either of these two notions, these factors could then be assessed in relation to each other when designing a line. The object should be to keep vibration intensity within safe limits and at the same time, retain sufficient endurance capability economically balanced in such a way as to ensure a sufficiently long period of service on the part of the installation.

9. Vibration intensity can be reduced by the use of suitable damping devices. Similar auxiliary equipment can be used in order to raise the endurance capability of the line. Such equipment is logically to be considered a part of the line itself. In some cases damping devices will raise the endurance capability of a line at the same time as it reduces the vibration intensity.

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3. Definitions, see figure 1.

10. Cable:

D	External diameter of the cable.
w	Weight per unit of length of the cable.
γ	Specific weight of the cable material.
I_D	Moment of inertia with respect to a diameter of the cross-section of the cable.
E	Modulus of elasticity.
U	Modulus of flexibility.
μ_c	Coefficient of internal friction of the cable when exposed to flexion.
δ	Logarithmic decrement of cable.
σ_u	Specific ultimate strength.
σ_{end}	Specific endurance limit.
σ_{creep}	Specific creep limit.
O_c	Factor depending on the surface of the cable.
$O_{str.}$	Factor depending on the surface of the strands of the cable.

11. Fixing devices and conditions in the cable at fixing points.

ν	Articulation factor of the fixing clamp.
η	Transmission factor of the suspension clamp.
L_c	Length of the cradle of the suspension clamp.
h	Difference in level between the cable axis and the pivoting axis of the suspension clamp.
μ_r	Friction against rotation in the pivot of the fixing clamp.
I_r	Moment of inertia with respect to the pivoting axis of the fixing clamp.
F_c	Clamping force of the fixing device.
β	Angle of entry i.e. difference in angle of entry formed by the tangents to the chain curve at both sides of a suspension clamp.
R	Radius of curvature of the cable at the entry of the fixing clamp.
S_f	Damping efficiency of fixation.
C_f	Reflection purity factor of fixation.

12. Span.

L	Length of span.
T	Total mechanical tension of the cable.
σ	Static specific stress of the cable material.
ε	Specific elastic elongation.
$c=\frac{T}{w}$	Parameter of the span.
C_t	Terrain factor.

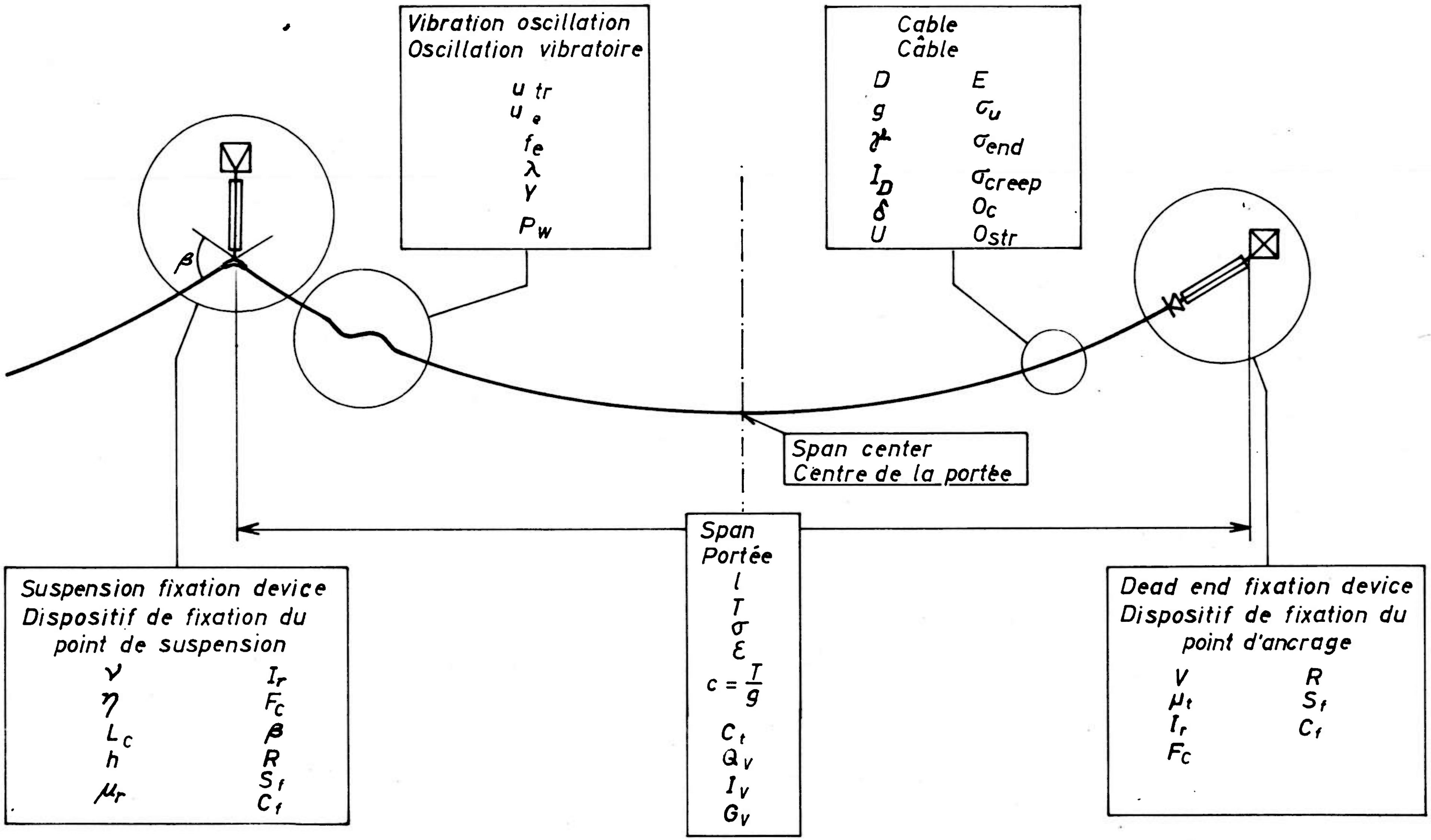
13. Vibration oscillations.

u_{tr}	Speed of propagation of a transverse impulse on the cable.
u_l	Speed of propagation of a longitudinal impulse in the cable.
f_e	Proper frequency of the transverse oscillations or of the transverse impuls.
Y	Double amplitude of the transverse impulse.
λ	Wave-length of the transverse impulse.
P_w	Vibration power introduced in the cable per unit of length.

DEFINITIONS

Fig. 1

Characteristics of cable, span, fixation devices and vibration oscillation
Caractéristiques de câble, portée, dispositifs de fixation et oscillation vibratoire



4. Vibration Intensity.

4.1. Generation of vibration.

14. So far the best explanation of the generation of vibration is assumed to be that based on Bénard - Kármán's theory of turbulences, i.e. when a cylindrical body is rigidly supported in an air stream, turbulences will be released from the leeward side of the cylinder with a frequency which can be expressed by the formula:

$$f_s = S_o \frac{V}{D} \tag{1}$$

where:

$V =$ air stream velocity component perpendicular to the axis of the cylinder.

$D =$ diameter of the cylinder.

$e =$ cinematic viscosity of the air.

$S_o = f\left(\frac{VD}{e}\right) =$ Strouhals number.

$\frac{VD}{e} = R_e$ = Reynolds number.

For ordinary overhead transmission line conductors and within an actual range for the Reynolds numbers the Strouhals number varies between 0.185 and 0.22, the value of 0.2 being most frequently used.

15. The alternating vortices indicate an alternating pressure distribution around the cylinder tending to vibrate the cylinder transversely to the air stream.

16. If such vibration is allowed, for example by mounting the cylinder on springs, the transverse motion tends to control the vortex shedding. Experiments have shown that the vortices are shed at or near the end of the amplitude range of the cylinder. The influence of vibration on the vortex trail has been investigated by Steinman [15] who introduced a Strouhal number dependent on the vibration amplitude,

$$S = \frac{1}{q} S_o \tag{1a}$$

where q is the amplification factor of the vortex trail.

$$q = 1 + \frac{Y}{1.3D} \tag{1b}$$

(Y is double amplitude of vibration).

17. It is thus seen that the shedding frequency decreases as the vibration amplitude increases. Together with the resonance curve of the vibrating object this partly explains the so-called "locking in" effect reported by many investigators. Within a critical range of wind speeds the object vibrates in its natural frequency in spite of formula (1) which therefore is correct only if the object is at rest.

18. The natural frequencies of a normal span lies so close that the frequency of the vortex shedding for steady winds within the normal range will correspond closely to some mode of vibration.

19. Within the critical range of wind velocities, it is assumed that vortex shedding take place over a certain length of the span. Due to greater or smaller variations in the air stream, the forces acting on the cable at rest are irregular, and are then not able to produce significant vibration.

20. Now suppose that at a certain place in the span the air stream is so uniform over a short length that a periodic motion of small amplitude takes place. According to the dynamic laws, this motion introduce travelling waves to both sides of the source.

21. The travelling waves bring the transverse motion with its proper frequency to other places of the span, and due to the "locking in" effect the exsisting, irregular, vortex shedding on a particular place changes to the frequency of the source. Thus, as the travelling waves proceed, more and more energy is introduced by the wind, and the transverse motion of the cable at a certain place is amplified.

22. At the ends of the span the waves are reflected and returned to the source which is now extended to a larger part of the span, namely the part corresponding to the width of the vibration generating air stream. The waves are reflected at a phase angle depending on the dynamic characteristics of the fixing device.

23. If the waves are reflected without loosing too much energy in damping devices and end construction elements, and without beeing transferred to waves of other frequencies, or to oscillations of other character (for instance torsional oscillation), the vibration tends to build up. If the waves is not reflected at all, or if they are reflected in an improper form, the attempt to start vibration would be a failure.

24. In the next turn a new attempt, perhaps at another place of the span and with another starting frequency will be made, and so on until at last, if possible at all, the travelling waves are acting together, forming a more or less irregular oscillation which is named vibration.

25. Owing to the "locking in" effect there will be "preferred" frequencies corresponding to the dominant natural frequencies of the system which are dependent on the characteristics of the span, i.e. the characteristics of the cable, towers, insulators, clamps etc.

26. The vibration of a span does not normally start instantly. Usually there is a period of building up, a period of more or less stationary vibration and finally a rather short period of decay.

27. The building up period can be explained by assuming that the wind gradually changes from a turbulent state to a more or less uniform air stream capable of generating vibration. As the front of the air stream passes the span, numerous attempts to start vibration will be made. But because the air-stream changes noticeably with time, both in structure and in velocity, no steady vibration will occur until the air stream has become laminar and with velocity variations within the critical range where the "locking in" effect is in force.

28. The vibration in the "stationary period" is very seldom in the form of pure standing waves, it rather forms a beat pattern. This is attributed to generation of vibration by two or more wind fronts of different velocities [16].

29. Similar to the "building up period", the "decay period" may be explained by assuming a change in the properties of the air stream.

30. Tests in wind tunnels have confirmed formula (1) for the frequency of the vortex shedding, and also the modification indicated by (1a) and (1b) if vibration is allowed. In a tensed cable, as in transmission line span arrangements, however, it is very difficult to state whether the expressions are strictly correct or not. According to the reasoning above, the final vibration frequency depends on the frequency at the point of starting. Because the "locking in" effect occurs within a limited range of wind speeds (40 - 50%) it may be expected that a corresponding variation will be found if formula (1) is checked against measurements. Moreover the actual wind velocity is very difficult to determine. The micro structure of the air stream might be of importance in connexion with vibration. However, information on this subject is not easily available, see CIGRÉ - report No.236/1964 [13].

31. We might possibly be satisfied by stating that vibrations are due to the movement of air perpendicular to the cable, and that the nature of these oscillations depends on the velocity of the air stream and probably also on its structure. Vibrations might occur when the velocity of the air stream lies within a particular range and when the air stream has a certain structure. Formula (1) represents an approximate expression, indicating the relationship between the frequency of oscillation, the velocity of the air stream and the diameter of the conductor.

32. It should be noted that in some special cases important vibrations might occur and cause trouble even when the air stream velocities lie in the range of 20 to 35 m.p.h., i.e. 9- 17 m/s corresponding to frequencies of 50-90 p.p.s. (Ref. Sacramento River crossing of the Pasific Gas and Electric Company and fjord crossings in Norway.)

33. In this respect the air stream is actually of interest only as far as it generates vibrations. Nevertheless more detailed information on the structure of the air stream, would be of interest. Here I suggest that persons dealing with micro-meteorology might be of help to us.

34. I should also mention that vibrations might be started by other effects, as for example sudden changes (rises) in the temperature in the cable, and, in other cases, corona discharges from the conductor surface.

4.2. Nature of the vibration oscillations.

4.2.1. Transverse oscillation.

35. The propagation speed of a transverse impulse along a tensed suspended cable forming a span is given by the formula:

$$u_{tr} = \sqrt{\frac{T.g}{w}} = \sqrt{c.g} = f_e \lambda \qquad (2)$$

where:

g = acceleration due to gravity.

36. Vibrations are very seldom registered as pure stationary oscillations. Normally pulsations appear showing a frequency of about ten percent of the frequency of vibration oscillations. As a rule the frequency varies a little from pulsation to pulsation and even within the same pulsation. For a theoretical approach to the vibration problem, vibration oscillations can conveniently be considered as beeing built up of series of transverse, sinusoidal impulses.

37. Standing waves result when two waves of equal wave-length and amplitude travel simultaneously and in opposite direction along the cable.

38. It should be noted that the most significant characteristics of a transverse oscillation on tensed suspended cables forming spans are the speed of propagation of the transverse impulse

u_{tr} - given by formula (2) - and the "steepness" of the impulse. The steepness of the transverse impulse is expressed by the ratio $Y/2\lambda$, which is again proportional to the vibration angle, α i.e. the maximum angular deflection of the cable at a node point. The frequency may show several different values.

39. The importance played by transverse oscillations in vibration complexes is obvious. I shall later on return to this when dealing with stresses in the cable material and damage caused by vibrations.

4.2.2. Longitudinal oscillation.

40. There must be a certain connexion between the transverse and the longitudinal state of oscillation. The speed of propagation of longitudinal waves, i.e. the speed of sound, in metallic materials, may be regarded as a characteristic constant of the material, which can be expressed by the formula:

$$u_{l} = \sqrt{\frac{E \cdot g}{\gamma}} \qquad (3)$$

This formula is valid in the frequency range below 10 kHz, i.e. in the range of sound and infra-sound. For aluminium and steel $u_{l} \approx 5000$ m/s, and for copper $u_{l} \approx 3900$ m/s.

41. Combined with formula (2) the following relation is obtained:

$$u_{tr} = u_{l}\sqrt{\varepsilon} \qquad (4)$$

42. If a transverse impulse is introduced to a span of rather short length, a practically instantaneous change of tension along the whole span will be the result, i.e. a transverse oscillation of the type $\frac{\lambda}{2} = L$. In longer spans such an impulse of tension causes a transverse impulse of considerable wave-length [6]. After several reflections at the ends of the span a transverse impulse of this kind will grow successively less pure, i.e. the result may be a transverse oscillation of high frequency. Thus it is possible that shock-like variations of the tension of a cable may cause vibrations. This hypothesis might be of interest for the understanding

of the starting mechanism of the vibrations, especially in connexion with the momentary "give" which can be observed when the temperature in the cable suddenly rises. Further, it is possible that high-frequency variations (corresponding to vibration frequency) of the tension of the cable may cause material fatigue, especially in connexion with "fretting". This subject will be discussed later in this report.

4.2.3. Torsional oscillation.

43. Any change in the torsional state of a tensed suspended cable forming a span occurs rather slowly. And because the moment of inertia with respect to the axis of the cable is of reduced value, torsional oscillations causing material fatigue may hardly occur. However, if the cable is coated with snow or ice, the case is different. Under such circumstances important torsional oscillations have been observed. This type of oscillation may cause wear and tear between different layers of strands. Such wear and tear is probably more harmful to the cable than any torsional material fatigue.

44. On fjord spans torsional oscillations of a very low frequency have been observed. However, this type of oscillation does not seem to be related to vibration oscillations and should normally present no problem.

45. The characteristic torsional quality of a cable may be utilized to damp the vibrations, cf. torsional dampers.

4.3. Factors influencing the vibration intensity.

46. The natural vibration intensity shown by a tensed suspended cable forming a span depends presumably on the following qualities:

a) The oscillation energy which can be absorbed by the vibrating cable. Here the micro-meteorological circumstances - the air stream probably beeing influenced by the topographic features, including the vegetation of the surroundings - should be taken into account.

b) The characteristic properties of the cable and the cable material.

c) The design of the span, i.e. silhouette and type of tower and crossarms, angle of entry β, etc.

d) The characteristics of the fixing devices, for example the transmission factor η of a suspension clamp.

4.3.1. Oscillation energy absorbed by the vibrating cable.

47. As mentioned previously it may be assumed that vibrations are due to a movement of air around the cable, further, that the nature of this air stream will decide to what degree vibrations will be generated in the cable. Undoubtedly meteorological and topographical conditions are involved in this matter, but the actual significance of these factors is not known in detail. It is generally assumed that lines running across flat or level terrain without trees or other tall vegetation are most exposed to vibration. In more rugged terrain vibrations normally occur in relatively short stretches along the line. Under these circumstances it is difficult to foresee the vibration intensity along a projected trace of a line, with a view to taking precautions against the vibration difficulties already at the design stage.

48. Vibrations are maintained by energy taken from the air stream. Two Australians, Bate and Callow, presented in 1934 the following formula giving the energy of oscillation which is introduced to a tensed vibrating cable forming a span:

$$\Delta E = C_B' \cdot d \cdot V^2 \cdot D^{0,5} \cdot Y^{1,5} \cdot \lambda/2 \qquad (5)$$

where:

ΔE = oscillation energy input per loop per cycle

C_B = constant

d = air density

49. The formula may be rewritten to express the power input per unit of length. Further the wind velocity, V, may be substituted by using the Strouhal formula (1). Air density is taken as a constant:

$$P_W = C_B'' \cdot f^3 \cdot D^{2,5} \cdot Y^{1,5} \qquad (6)$$

50. Instead of using the double amplitude Y, it may be advantageous to use <u>the free span vibration angle</u>, i.e. the maximum angular displacement of the cable at a node. It is assumed that the vibration angle also reflects to what extent the cable is exposed to vibration bending stresses near the fixation point.

51. Assuming steady state sinusoidal oscillations the following relationships are obtained:

$$\alpha \approx \left(\frac{\pi}{\lambda}\right) \cdot Y \tag{7}$$

Further:

$$f \cdot \lambda = u_{tr} = \sqrt{\frac{T \cdot g}{w}} = \sqrt{\frac{\sigma}{\gamma}} \cdot \sqrt{g} \tag{8}$$

52. By substituting (7) and (8) into formula (6) the Bate power formula is modified to:

$$P_W = C_B''' \cdot f^{1,5} \cdot D^{2,5} \cdot u_{tr}^{1,5} \cdot \alpha^{1,5} \tag{9}$$

53. With reference to formula (12) it has been pointed out that the wind velocity rather than the frequency should be used in power expressions [17]. By using the Strouhal formula again, formula (9) is transferred to:

$$P_W = C_B'''' \cdot V^{1,5} \cdot D \cdot u_{tr}^{1,5} \cdot \alpha^{1,5} \tag{10}$$

54. Most people are perhaps not so familiar with the transverse wave velocity u_{tr}. As seen from (8) u_{tr} is composed from the mean spesific stress, σ, in the cable, and the mean spesific weight, γ, of the cable material. By substitution of u_{tr} the Bate power expression may be finally written:

$$P_W = C_B \cdot V^{1,5} \cdot D \cdot \left(\frac{\sigma}{\gamma}\right)^{0,75} \cdot \alpha^{1,5} \tag{11}$$

55. The Americans <u>Farquharson</u> and <u>Mc Hugh</u> besides <u>Caroll</u> were of the opinion that the air stream velocity should appear in the power formula with the third power. The two first mentioned presented the following formula:

$$P_W' = C_F' \cdot f^3 \cdot D^2 \cdot Y^2 \cdot F(Y/D) \tag{12}$$

Here F(Y/D) = function of Y/D. From the original paper [3] this function may be written for $Y/D < 0{,}36$:

$$F(Y/D) = 1 - 2{,}955 \left(\frac{Y}{D}\right) + 4{,}095 \left(\frac{Y}{D}\right)^2 \tag{12a}$$

As (Y/D) increases from 0 to 0,36, F(Y/D) varies from 1,0 to 0,437.

56. Similar to the Bate power formula, the formula (12) may be modified to use the vibration angle as the variable:

$$P_W' = C_F'' \cdot f \cdot D^2 \cdot u_{tr}^2 \cdot \alpha^2 \, F(Y/D) \tag{13}$$

or, by using the wind velocity instead of the frequency as the proper parameter:

$$P_W' = C_F''' \cdot V \cdot D \cdot u_{tr}^2 \cdot \alpha^2 \, F(Y/D) \tag{14}$$

and finally:

$$P_W' = C_F \cdot V \cdot D \cdot \left(\frac{\sigma}{\gamma}\right) \cdot \alpha^2 \cdot F(Y/D) \tag{15}$$

57. Under these circumstances the value of P_W should be understood as the oscillation power - the vibration energy - which can be absorbed by a tensed cable forming a span. Consequently, these formulas may indicate the importance of different characteristic qualities of the cable as well as of the span for the probable intensity of vibration when the air stream is of such a nature that is causes vibration.

58. The length of the span is certainly a factor of importance for the amount of possible vibration energy introduced to the span. Here we are entering a field linked with micro-meteorology. The question is, what is the maximum extent, l', i.e. the width, along the span, of an air stream having a nature such that vibration can be produced? To the best of my knowledge no extensive investigations in this field related to vibration research have yet been undertaken. It

seems natural that l' should depend on topographical conditions and vegetation. However, vibrations may be observed at some places where the topography or the vegetation logically indicate that little or no vibration should occur.

59. The most intensive vibrations should be expected in such cases where the length of the span corresponds to the width of the air stream generating vibration. If this supposition is correct, less violent vibrations should consequently be expected on spans longer than l' at the actual spot. However, the duration of the vibrations may be extended in such a case.

60. This question seems to be of great importance especially when dealing with spans of extreme length. However, comprehensive and complicated investigations will have to be carried out before a reliable answer can be given.

61. The other factors involved in the energy formulas are examined in the following paragraphs.

4.3.2. Cable and cable material characteristics of importance to the vibration intensity.

62. The most important characteristics of the cable that are of importance to the intensity of vibration are assumed to be:

Specific static stress of the cable material.
Specific weight of the cable material.
External diameter and surface condition of the cable.
Rigidity and specific damping of the cable.

63. In the following is mentioned the influence these characteristics are believed to exert on the intensity of vibration.

64. Specific static stress of the cable material.

According to formulas (11) and (15) the intensity of vibration of the span should increase proportional or nearly proportional to the stress of the cable material. Its influence on the endurance capability of the span will be discussed later in this report.

65. Specific weight of the cable material.

Cables built up of light materials should be more exposed to vibration than cables of heavy material, which is expressed in the energy formulas by the power minus (0.75 to minus 1) of the specific weight of the cable material.

66. External diameter of the cable.

According to the above formulas the power input appears to be proportional to the external diameter of the cable. This dependence, which seems logical, is confirmed by the common experience that large diameter cables are more likely to vibrate than smaller cables. Together with the influence of the cable weight, the influence of the diameter should be remembered when considering expanded or other light type conductors.

67. Surface condition of the cable.

The external form of cross section of the cable influences the intensity of vibration. With vibration oscillations of small amplitude the surface condition is of negligible importance, but with increasing amplitudes cables having a cylinderical cross-section and a smooth surface can absorb more energy than for instance a stranded cable. This theory has been verified by laboratory tests and is also confirmed by field experience. Consequently, as far as vibrations are concerned, cables with a smooth surface or with small-gauge strands in the outer layer should be avoided.

68. Rigidity and internal friction of the cable subjected to flexion.

An account of the rigidity and internal damping of the cable is given in an Appendix to this report. From this study some conclusions concerning the intensity of vibration can be mentioned.

69. a) The rigidity of the cable is a factor of importance to the steepness of the transverse impulse, i.e. the relating vibration angle (cf. also the power formules (11) and (15)). Consequently, vibration of higher frequencies are assumed to have smaller amplitudes on rigid cables compared with those on flexible ones, provided the internal damping is the same.

Owing to manufacture, winding on the spool and mounting, the rigidity of the cable must obviously be cept within certain limits.

Further the following condusions can be drawn concerning the internal damping of the cable:

b) The internal damping of a cable submitted to flexion decreases with increasing tension.

c) The internal damping of a cable increases with increasing amplitude of the transversal oscillation. Consequently the amplitude is limited, in general to the maximum value of 80 per cent of the radius of the cable.

4.3.3. Characteristics of the fixing devices of importance to the vibration intensity.

70. With respect to vibrations, a suspension fixing device can be characterized by the following two factors:

η: The transmission factor of the suspension clamp. This factor indicates the relation between the amplitude on either side of the clamp of a transverse impulse which is passing through it, i.e. the coupling between adjacent spans.

At anchoring points no such transmission takes place.

ν: The articulation factor of the fixing clamp indicated by the relation between two angles, namely the angle between the tangent to the curve which represents the form of the cable where it leaves the clamp respectively at a node point and the tangent to the chain curve at the corresponding points.

71. For simplicity's sake it is supposed that no static bending stresses occur in the cable even at the fixing point. Thus the articulation factor indicates to what extent vibration may cause bending stresses in the cable where it leaves the fixing clamp.

72. As the articulation factor is assumed to be practically without importance to the intensity of vibration, I shall later on in this report return to this quality of the fixing device.

73. η increases very closely in proportion to the length L_c of the cradle of the suspension clamp, while it is almost independent of the difference in height h between the axis of the cable and the pivoting axis of the clamp, when h is kept within practical limits. Furthermore the moment of inertia of the clamp I_r, with respect to the pivoting axis has a very slight influence on η (ν is however more influenced by this characteristic). Friction in the pivot of the clamp μ_r, is assumed to be more important, especially with rigid fixing points, such as post or pin insulators.

74. The value of the transmission factor also indicates to what extent vibration energy may dissipate through the suspension points to adjacent spans. Because the value of η very seldom exceeds 0.15 to 0.25 for ordinary models of suspension clamps, the effect of such an energy dissipation is of little importance. However, with very long cradles, giving values of η in the range of 0.4 to 0.5, the dissipation of energy to adjacent spans may cause a noticeable reduction of the intensity of vibration in the span considered.

75. With dead ends the fixing arrangements, i.e. the dead-end clamp, insulator chain, jumper etc., will absorb energy from the vibration oscillation. Thus, the intensity of vibration in spans with dead ends is assumed to be less than that of spans with suspension clamps at both ends.

76. Fixing devices of any construction will cause irregularities in the oscillations if they do not represent a distinct reflexion

point. Vibrations or other type of oscillations acting in resonance with oscillations in tower bodies should be mentioned in this connexion. Difference in "oscillation coupling" between one cable in a span and the tower in relation to an other cable in the same span may in some cases cause a difference in vibration intensity of the different cables in the same span, [6] and [13].

4.4. Bundle conductors vibration.

77. Bundle conductors are normally less liable to vibrate than single conductors. It has been reported that a two conductor bundle vibrates at an amplitude of about 50% and with a duration of 20% compared with a single conductor of the same size. This reduction is attributed to mutual damping in the bundle, [20]. The design, number and placement of spacers seems to be an important factor.

5. Endurance capability.

78. Previously I have mentioned some peculiarities of vibration oscillations. To recapitulate, the transverse vibration oscillations can easily be observed, while the corresponding longitudinal oscillations of similar frequency can only be recorded by suitable instruments. In this chapter I shall deal with stresses in the components or materials of the line caused by the vibrations. Generally, only the transverse oscillations are considered, longitudinal oscillations are assumed to be of negligible importance.

79. The vibrations produce dynamic stresses of flexure and tension causing fatigue of the cable material, failure or wear damage. These troubles occur in the cable at or near the fixing points or at points where "dead" masses of sufficient magnitude are attached to the cable. Damage caused by vibrations never appears in the free span unless the cable or the strands at any point are considerably weakened. The flexure stresses caused by vibrations in the cable where it hangs free in the span are very small in comparison with similar stresses acting in the cables at or near where it leaves the clamp, if the fixing device is

capable of setting up moments to counteract the bending moments in the cable.

80. It is difficult to state analytically or even in terms of measurement the flexure stresses caused in the different strands of the cable. Within a certain interval these stresses depend upon the rigidity of the cable, the rigidity of the cable depending upon the tension and the radius of curvature. The phenomenon called "unsticking" (French: décollement) of the cable submitted to bending should also be remembered.

81. Fatigue rupture or damage may appear in the hardware and insulator strings, as well as in the tower components.

82. Stresses of this kind are however considered to be of secondary importance compared to those responsible for difficulties in the cable itself.

5.1. Factors influencing endurance capability.

5.1.1. Factors characterizing the fixing devices.

The articulation factor, ν.

83. Previously, see 4.3.3., I have mentioned the characteristics of the fixing devices which are assumed to be most important to the intensity of vibration. A definition of the articulation factor is given in the above chapter. This factor vizualizes fairly well how the cable is submitted to flexure stresses at the fixing point, yet the second derivative of the function representing the curve formed by the cable would mathematically present a more correct expression of such flexure stresses.

84. The value of $\nu = 0$ corresponds to completely rigid fixation, while $\nu = 1$ represents the "knife edge" pivoted dead end, i.e. a fixation which gives no additional bending of the cable when submitted to transverse oscillations. A suspension

type fixation, for example a suspension clamp, gives a maximum value of $\nu = 0.5$. This value of ν is practically independent of the length of the cradle of the clamp. Consequently vibrations are expected to cause more trouble at suspension points than at dead ends, a fact which is also proved by experience. This point is especially important when dealing with spans of extreme length, e.g. river crossings and fjord spans, see [14].

85. Friction in the pivoting of the clamp reduces the value of the articulation factor. The effect of such friction is assumed to be more important with shorter lengths of cradle.

86. The articulation factor varies moderately with an increase in the difference of level between the centre axis of the cable and the axis of the pivot.

87. When a transverse impulse passes the clamp, a phase shift takes place, i.e. a time lag which increase with the moment of inertia I_r of the clamp. This phase shift causes an extra bending of the cable. Consequently the moment of inertia I_r of the clamp should be retained at a relatively low value.

Static radial compressive stresses in cable:

88. At the fixing points the cable will be submitted to radial compressive stresses partly due to clamping forces and partly due to the weight of the cable, the latter increasing with increasing value of the "angle of entry", β. The clamp should be designed in such a manner as to secure even distribution of these compressive stresses and preferably in such a way that the flexural stresses resulting from the alternating bending of the cable are kept to a minimum at the location where the cable is submitted to static radial compressive stresses. Fretting damage or surface deformation caused by bad clamp design should also be borne in mind.

89. In this connexion it is probably worth mentioning that the rigidity of the cable is increased when it is radially

compressed. I shall later in this report return briefly to this question, see paragraph 92.

90. Fatigue ruptures of the strands occur frequently at points where the strands cross each other. This is logical because of the concentrated compressive stresses at such points.

<u>Static flexural stresses in the cable.</u>

91. Such stresses occur at points where the cable rests in a bent position on the cradle of the clamp or where the design of the clamp is such that the cable leaves the fixation in a direction which does not follow the tangent to the chain curve at the point of fixation. In the last case the alternating bending stresses caused by the vibrations are superimposed on the static flexural stresses of the cable. It should be remembered, however, that the rigidity of the cable might be considerably reduced when submitted to static bending, see Appendix. When the rigidity of the cable decreases, the flexural bending stresses increase accordingly. This fact may also help to explain why fatigue failures more frequently occur at suspension points than at dead ends where the cable is normally not submitted to static bending.

92. From these considerations the conclusion may be drawn that the design of the fixing device should preferably be such that the cable leaves the clamp in a direction which follows the tangent to the chain curve at the point of fixation. At any rate it would be advisable if the rigidity of the cable could be increased where it leaves the clamps by adding a static radial compressive force to the cable at this point.

93. Creep of the cable material might in time cause a reduction of the static flexural stresses. This fact is probably of some importance especially when dealing with aluminium cables.

5.1.2. Cable characteristics of importance to the endurance capability.

Rigidity of the cable.

See chapter 5.1.1.

94. It should be noted that, when assuming constant cross-sectional area of the cable, the rigidity of the cable increases with increasing diameter of the strands (the number of strands decreasing).

Strength characteristics of the cable material.

(a) Endurance.

95. If the time up to breakdown caused by fatigue, or the number of bending cycles, is plotted against the amplitude of the alternating bending stresses, the form of the curve is fairly well represented by the function:

$$\tau = C_1 \cdot \frac{1}{f} \cdot e^{-C_2 \cdot a} \qquad (16)$$

where:

τ = time up to breakdown.
f = frequency of oscillation.
a = amplitude of bending stresses.
C_1 and C_2 = Constants.

96. Most likely there is no need for a total suppression of vibrations. The problem is solved if the required time up to breakdown can be obtained by keeping the amplitude of the alternating stresses or the number of bending cycles within certain limits. However, one should certainly be aware of fretting, see paragraph 99. The endurance limit of a cable is difficult to state. Tests made on simple strands do not always give trustworthy results, cf. the "Rotating beam - method". Such tests should probably be executed on complete cables which are submitted to longitudinal stress and fixed by clamps of a defined design. This seems logical when bearing in mind what is mentioned in 5.1.1.

Surface condition of the cable material.

97. A cable made of fine strands is assumed to be more susceptible to fatigue caused by vibrations than a cable made of larger strands when considering cables of equal cross-sectional area. Two reasons may be adduced. Firstly, the former has a larger surface of material than the latter, which provides scope for more irregularities in the surface. Secondly, the material in itself is normally more brittle because of the higher degree of deformation exposed during the drawing of the strand.

Resistance to corrosion of the material.

98. This quality is another factor of importance to the surface condition of the cable material or, in other words, to the endurance limit of the cable. Hence, corrosion should be prevented at such points on the cable where fatigue failures might be expected.

Fretting or fretting corrosion should certainly also be noted.
99. Ordinary corrosion occurs in the contact areas between strands of different layers of the cable. The same locations are also exposed to fretting, which may be defined as the surface damage that occurs when two solid surfaces are contacted under relatively high loads with relatively small vibratory motions. Fretting reduces in it self the endurance limit of the cable. Therefore it would be desirable if this destructive effect could be reduced in some way or other, for instance by the use of grease applied to the contact areas by a sort of injection in the cable at the clamping location.

b. Specific breaking strength of the cable material.

100. If a cable is made of high strength materials, the specific every-day stress is normally restricted to relatively high values. Vibration troubles should first of all be expected in cases where such cables are used where the relation between the endurance limit and the breaking strength of the cable presents a low value.

c. Creep.

101. The creep of the cable material results in unevenness of the static stresses tending in time to be reduced, cf. for instance the static bending stresses in the cable in the region of the suspension clamp. Creep might influence the endurance limit of the material, which, however, is hardly a very important point.

d. Difference in static stress of various strands.

102. Such unevennesses might occur during the manufacturing of the cable. The tension can be unequally distributed among the different strands of the same layer or among strands of different layers.

103. When the pitch angle of the various layers is different, the stresses in the strands of different layers tend to change in relation to each other when the tension of the cable is altered, for example with variations of temperature. This might to some extent explain why the strand failures seem to occur at random over the cross-section. Creep of the material might even cause a reduction of such unevennesses of stress.

e. Tension of the cable.

104. The static stresses caused by the actual tension of the cable play a decisive role in endurance capability. The endurance limit of metallic materials decreases rapidly with increasing static stress when the alternating stresses are superimposed on the static stresses. Consequently the EDS value should be kept under a certain limit, depending on the vibration intensity of the span considered. EDS limiting values, which can be regarded as safe under various conditions, have been recommended by the working group dealing with this subject within CSC 6. Others have given some indications on the reduction of the number of bending cycles leading to fatigue when increasing the value of EDS.

6. Quantitative relationships in the vibration complexity.

105. In the previous chapters each parameter considered to be of predominant importance in the vibration complexity have been discussed. In table 1 all these factors are registered together with an indication of their influence on the two notions: Natural vibration intensity and endurance capability. As yet little attention to the quantitative relationships between the different parameters has been paid. Such relationships could be stated by analysis founded upon theoretical or empirical methods. I still think it is appropriate to use the two same notions:
Vibration Intensity and Endurance Capability:

First I should call to mind that Mr. Holst, see [11] already in 1931 introduced an empirical expression $\frac{T \cdot D}{w} = c \cdot D$ which was intended to give a rough indication of the risk related to vibration of a span. Some years later Miss Artini [9], presented a similar formula. The introduction of such formulas represents an adequate approach to the actual problem, namely how to foresee the vibration intensity of a span. But these formulas are certainly not sufficiently accurate, and do not involve all major factors, at least not in their right proportion.

Vibration Intensity.

106. The vibration level of a span depends primarly on the balance of power taken from the wind and the power dissipated in the cable, fixations etc. Together with the vibration level, the duration of vibration and the vibration frequency are the most important factors which determine the life time of the transmission line.

107. If the vibration level, expressed by the vibration angle, and the frequency was constant during a period of time τ, the accumulated vibration in that period may be written:

$$Q_v' = \alpha \cdot f \cdot \tau \qquad (17)$$

The mean vibration intensity of the same period is defined as:

$$I'_v = \frac{Q'_v}{\tau} \qquad (18)$$

or in words: The accumulated vibration per unit of time.

108. Now the vibration angle is never constant during a registering period. Suppose that it is possible to group the vibration angle into groups, α_1, α_2, α_3 ... within which the magnitude may be assumed to be constant.

109. Further, assume that the cycles of vibration of the various groups are determined to n_1, n_2, n_3 ... Then the accumulated vibration is:

$$Q_\tau = \alpha_1 n_1 + \alpha_2 n_2 + \alpha_3 n_3 + \ldots + \ldots = \sum_{p=1}^{p_o} \alpha_p n_p \qquad (19)$$

Here p_o is the number of groups.

110. The vibration intensity in the period considered is accordingly defined as:

$$I_\tau = \frac{Q_\tau}{\tau} \qquad (20)$$

111. It is possible, from data on wind velocity, cable dimensions, internal and other damping to calculate the expected vibration angle of a span at a particular wind velocity.

112. To evaluate by theory the vibration intensity, however, would be rather difficult. It is well known that the same wind velocity, or frequency, does not always give the same vibration level. This may be attributed to difference in the width of the air stream from time to time. Further, the calculated vibration angle only refers to steady state condition which is rather the exception than the rule.

113. Finally the wind velocity varies with time in as well direction as in magnitude in an unpredictionable way unless statistical data are available.

114. However, taking all the significant parameters into account, the vibration intensity may be expressed in a general form:

$$I_V = F(V,t,D,\sigma,\gamma,L,\delta,S_c,C_c,O_c,C_t,U) \qquad (21)$$

115. Here the wind velocity V, and the time t, can not be controlled at the design of the span. All the other parameters are at least to some extent, under man's control. It seems therefore logical to find how the different design parameters make influence upon the vibration intensity. For this purpose formula (21) is rewritten:

$$I_V = F(V,t,\varphi(G)) \qquad (22)$$

116. Here the inner function φ is a function of the liability to vibration or the vibration liability of the span which again is a function of the design parameters. We might assume that the parameters defining the vibration liability appear in an exponential form. The problem is then to determine the exponents.

117. It is reasonable to assume that the vibration liability is proportional to the factors appearing in the wind power equations (12) or (15). Adopting eq. (15) and taking the function F(Y/D) equal to one, the diameter should appear in the power of + 1. Similarly the specific stress σ, will appear in the power of + 1 and the spesific weight in the power of - 1.

118. The influence of the span length has been discussed previously, see chapter 4.3.1. A quantitative analysis of this subject leads to the following conclusions:

119. The vibration energy introduced to a span is probably fairly exactly proportional to the length of the span, at any rate, when dealing with span lengths within certain limits.

120. When the vibrations are suppressed only by attenuation of oscillation energy in the cable itself, the total damping effect in the span is proportional to the span length as well.

121. Consequently, under these circumstances, the vibration intensity must be independent of the span length.

122. As attenuation of vibration energy more or less will take place in the end components, i.e. fixing devices, insulator strings, tower structures, etc., the vibration intensity is assumed to some degree to increase with increasing span lengths.

123. For the span length L the exponent 1.o. should then be adopted when dealing with span lengths of same order as the width of the front of the air stream generating vibrations. For longer spans the exponent is likely to decrease.

124. The logaritmic decrement of normal cables is usually small (in the order of 5.10^{-3}) [17]. The power dissipated in a vibrating loop is proportional to the logaritmic decrement. It seems therefore justified to give the log decrement the exponent -1.

125. The damping efficiency of the fixation devices S_f reflects the steady state power consumption at the fixation point. Since the power consumption is proportional to S_f, [5], it should appear in the power of - 1.

126. The clamp, insulator string and tower does not influence only by its damping efficiency. The reflection purity factor of the fixation, C_f is a factor of exponent 1 indicating to what extent the incoming wave is reflected in a proper form. A perfectly rigid clamp would have the value C_f = 1.0. C_f decreases if the reflected wave is distorted or transformed to other modes of oscillation.

127. The surface of the cable should be represented by a correction factor O_c with exponent 1.o. Reference [8] indicates the values given in table 1. These values actually represent <u>the amplitude</u> of different types of stranded cables in relation to the amplitude of a smooth cylinder of equal diameter.

128. One of the most difficult factors to handle is the terrain effect. Until now no sttampt has been made to state by a number the influence of the terrain. By comparing numerous test results, however, it should be possible to obtain a numerical measure of the terrain effect. Such comparison has been done [19] and indicates that the terrain factor $C_t \approx 1$ in very flat terrain near a large lake, $C_t \approx 0,5$ in very flat terrain and $C_t \approx 0,05$ in fairly flat treed terrain near a large lake (some buildings nearby). In a wood we probably may take C_1 near zero.

129. The influence of the flexural rigidity of the cable is difficult to state. It is assumed that the exponent should be negative, and of a value less than one. In the following the influence of rigidity is neglected.

130. The following expression may then be taken as representative for the liability to vibration of a span:

$$G = D \cdot \sigma \cdot \gamma^{-1} \cdot L \cdot \delta^{-1} \cdot S_f{}^{-1} \cdot C_f \cdot O_c \cdot C_t \qquad (23)$$

It is interesting to note that the three first factors appear in the same form as in the vibration risk formulae introduced by Mr.Holst [11].

131. It is known that the damping of a cable normally decreases as the tension increases. For simplicity sake, let us assume that the logarithmic decrement varies as the inverse of the tension. For a given span, the vibration liability then will vary with the second power of the tension. This is in good agreement with the results obtained by Mr.Edwards and his collegues [19].

132. If G according to (23) was calculated for a number of spans more or less exposed to vibrations, and assuming that the factors, which are deleted in these expressions, were fairly equal for all the spans considered, a quantitative and relative expression for the vibration intensity could be established.

133. It is of little sense to calculate G for a selection of spans if the natural vibration intensity can not be stated by measurements on the same spans. There is a need for measuring equipment for this use.

134. Information based on statistically collected data in this field would be valuable. Therefore great effort should be made to develop a simple and cheap, but at the same time sufficiently reliable, equipment for the indication of vibration intensity. If such equipment in a simple way could be placed preferably in every span along a line, the vibration intentisy could be registered and the need for additional damping could be stated. At the same time information concerning factors like climate and topography would be obtained.

135. Recommendations to investigators as to which types of instruments should be used and which measuring methods should be adopted to obtain trustable and comparable results should be given.

Endurance Capability.

136. A quantitative analysis of the endurance capability and the factors involved in this notion can be made similarly to that of the vibration intensity. Calculation of the endurance capability, to obtain numerical values, seems to be a too intricate problem to handle. We have to examine the quantitative relationships between different factors involved in this notion by empirical methods.

137. When including the most important factors under this notion on table 1, the following expression indicating endurance capability is obtained:

$$\phi = f\left(\frac{\sigma}{\sigma_u}, \frac{\sigma_{end}}{\sigma_u}, \nu, \beta, F_c\right) \qquad (18)$$

The following procedure could be adopted:
In a test arrangement a specimen of the cable is exposed to forced transverse oscillations of a particular frequency and

amplitude chosen within the range of actual vibrations. It should be possible to operate with varying static tension in the cable, and the fixing devices of the cable should be carefully designed and given a defined form. The object of the investigations should be to obtain numerical values representing the endurance capability. It seems logical to indentify this notion with the number of bending cycles of certain levels untill breakdown occurs.

138. In a research program all the factors which influence the endurance capability, according to table 1, could be varied in turn. In that way the influence of each factor could be verified and quantitative relationships established. Then, further investigations could be limited to determine the endurance capability only for especially interesting or actual arrangements.

139. The cases ν = 1.o and ν = o are fairly easy to arrange for testing. Values of ν in the intermediate zone are more difficult to handle.

140. In the case of ν = o, the influence of bending in the cable could be investigated by varying the angle of entry, β .

141. One main problem is now left, how to establish relationship between vibration intensity and endurance capability. This can be done through the formula (16) (page 24). However, several assumptions and simplifications have been adopted, so the result of such a theoretical analysis seems to be of reduced value. It does, however, give us a pointer to the course of the curves which can be traced with more confidence than when they are based entirely on experimental investigations.

The procedure could be this:

142. The endurance capability is determined mainly by experimental investigations as previously indicated.

143. The vibration intensity has to be determined in the real span as well as in the same testing span where the endurance capability is investigated.

144. Now, based on formula (16), or a similar one, the following relation can be established:

$$\tau_1 = \tau_0 \cdot \frac{f_0}{f_1} \cdot e^{c_2 (\alpha_{b0} - \alpha_{b1})} \qquad (19)$$

where:

τ_0 and τ_1 = time until breakdown when bending amplitude is α_{b0} and α_{b1} respectively and frequency is f_0 and f_1 respectively.

145. The product $\tau_0 \cdot f_0$ represents the endurance capability found by experimental investigations. Consequently, time up to breakdown can then be expressed by the endurance capability $\tau_0 \cdot f_0$ and the vibration intensity represented by the function $\frac{1}{f_1} \cdot e^{-c_2 \cdot \alpha_{b1}}$ which has to be examined on the actual span. Endurance capability is assumed to be the same in the testing arrangement as in the actual span. A quantitative relationship of this kind is not valid when other factors like ν and σ are different in the two cases. It would then be necessary for further analysis of the problems, and setups of empirical formulas similar to (16) to be undertaken.

7. Conclusions.

146. Future works with vibration problems should in my opinion be performed according to the following principles:

a. Discussion and verification of the theories presented in this report. Judgement of what is said about the importance played by the different factors involved in vibration.

b. Investigations of the nature of the vibration generating air stream.

c. Experimental investigations of the endurance capability of cables and how this notion is influenced by static tension, the proper characteristics of the cable, of fixing devices, angle of entry etc.

d. Preparation of a recommendation concerning measuring methods and possibly of a standardization of measuring devices, (See CSC 6-66-3).

Development of a simple, but at the same time cheap and reliable vibration indicator, which can be installed in a great number of spans to be able to chart the vibration intensity along a line, giving information about the role played by factors like topography, vegetation and climate.

e. Coordination of efforts of this kind and cooperation between authorities dealing with this subject. Circulation of a questionnaire: What sort of vibration studies and investigations are you doing and why? Replies should refer to the objections of and the vocabulary used in this report.

A N N E X

Rigidity and Internal Damping of Tensed Stranded Cables.

147. The rigidity of a beam is characterised by the modulus of flexibility (Dimension m^2 kp) :

$$U = E.I.$$

where

E = modulus of elasticity
I = moment of intertia with respect to a diameter.

The modulus of flexibility in this case is constant, independent of the beam's deformation, in any case for small deformations.

148. For a stranded cable the modulus of flexibility is not constant, but depends on tension and curvature as well as on the constant values representing material qualities (modulus of elasticity and shear modulus of elasticity), on the geometrical composition of the cable and on the internal friction of the cable when exposed to bending. Calculating the modulus of flexibility of a stranded cable is relatively complicated. In principle the result will turn out as shown in the figure. I have traced these curves for a 228 mm^2 ACSR cable after a calculation based on Lehanneur's theory [6, part 4], see also [10].

A number of interesting observations may be made on this curve.

149. The rigidity of a cable, i.e. its modulus of flexibility, is constant independent of tension and bending above a certain value of the radius of curvature. For small values of the radius of curvature the rigidity of the cable will be small. For curvature in the intermediate zone it will be seen that rigidity increases with tension. The marked reduction in the rigidity of the cable for decreasing radius of curvature is due to the fact that the layers of wire become "unstuck", i.e. the radial compressive forces in the cable cease. It

is possible to calculate the values for the radius of curvature where the unsticking of the layers of wire commences and where this effect is complete. Unsticking will first start with the outermost layers of wire.

150. With the help of the curve representing the modulus of flexibility as shown in the figure 2 I have made an approximate calculation of the radius of curvature in the cable at the fixation points and at the oscillation loop centre-point [6, parts 2 & 3]. In so doing I have ignored static bending stresses in the cable.

151. At rigid fixation points the radius of curvature of the cable will only be a fraction of the curvature radius at the loop centre point, where it presents the lowest value. The calculation shows that fairly marked "unsticking" of the layers of wire in the cable can be expected when the ratio $\frac{Y}{2\lambda}$ approaches maximum values occuring (10^{-3} , according to [11] (Mr. I.C. Holst). This explains the special sound which occasionally occurs at the cable's fixation points when it is exposed to violent vibrations. This sound is similar to the one obtained by striking two bundles of wire against one another.

152. "Unsticking" of the cable also explains why it may suffer internal abrasion, viz. between the layers of wire, at the fixation points.

153. For the same reason strand ruptures due to vibration will sometimes occur at a distance of a few centimetres from the cable's fixation point. Clamping will increase the rigidity of the cable at the fixation point, thus preventing "unsticking".

154. With regard to conditions at or by the fixation clamp the cable should therefore be constructed as rigid as possible. It seems senseless, however, to make the cable rigid merely because of desirable characteristics in the few centimetres of cable near the fixing clamp. Now the rigidity of the cable will influence the steepness of the transverse impulse,

i.e. the relationship $\frac{Y}{2\lambda}$ or α in formulas (11) and (15). As the propagation velocity of the transverse impulse is only slightly dependent on rigidity, vibrations of higher frequency will more easily occur, at any rate with considerable amplitudes, in flexible than with rigid cables. Mr. Holst found that steepness increased with increasing frequency, which by the way agrees with energy formulas (9) and (13), where introduced energy increases with increasing frequency. It is important, in other words, to avoid high frequencies, and this can be achieved by using rigid cables. Thus two reasons can be put forward for choosing cables of great rigidity. In practice, of course, certain limits must inevitably be set.

155. Let us now consider the factors which first and foremost decide the rigidity of the cable.

Cross-sectional composition of the cable.

156. Mono-metallic cables used as conductors on transmission lines are normally made homogenously, with strands of equal diameter with the layers cross-laid and with the number of strands per layer following the series 1 - 6 - 12 - 18 --. In poly-metallic cables each section is as a rule built up in a similar way.

157. It seems to be proved by experience that cables composed of coarse strands are less liable to vibration damage than those composed of thin strands. This is no doubt partly due to the fact that vibrations will be smaller, because the cable is rougher. Further-more the cable will be more rigid, a point whose significance has been mentioned above. With thin strands, too, the total material surface area is larger, which means greater possibility of surface unevenness. In addition the material becomes more brittle as a result of a higher degree of deformation during the drawing process.

Pitch angles of the strand layers and tightness of the cable.

158. The rigidity of a tensed cable decreases with increasing angle of pitch in the strand layers. The varying angle of pitch for the various strand layers will influence the rigidity of the cable when under tension.

159. Successive decreasing angles of pitch from innermost to outermost layers will result in the layers of wire being more firmly pressed together the more the cable is stretched. Excessive difference in pitch angles will result in undue differences in the specific tension on various strand layers.

160. The firmness of the cable also depends on how tightly the layers of wire are wound on during the manufacturing process.

161. When choosing the center strand with a diameter slightly larger than that of the other strands it helps to ensure that the cable is rigid under tension. In ACSR cables the steel core can likewise be made in such a way that it takes up a little more space than the corresponding hollow in the inner layer of aluminium.

Internal friction of a cable under bending; internal damping of the cable.

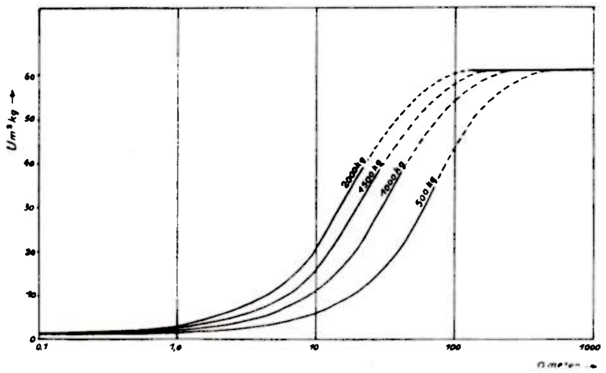
162. Internal damping of the cable depends on the friction between strands when the cable is exposed to bending. In such cases tightness of winding is important, as well as the coefficient of friction between the strands. If initial friction is large, bending moments below a certain value will cause no gliding between the strands, and consequently the work of friction will only depend on molecular friction in the material, i.e. it will be of a negligeable value. As the bending moments in the cable on the "free" span caused by vibrations oscillations are very small, the situation is very liable to arise where no gliding between strands occurs. In such cases we can speak of an elastic cable in contrast to an un-elastic cable when gliding takes place.

163. Internal damping of the cable depends on whether bending stresses due to vibrations overcome initial friction, so that gliding occurs. Friction tends to increase in time as a result of corrosion thus preventing gliding. To counteract this effect a moderate application of grease during the process of manufacture could be adopted. With the passing of time friction will also be changed owing to internal abrasion between strands and to creep of the material.

164. Internal damping of a cable decreases quite considerably with increasing tension. However, it increases with vibrations amplitude. This entails amplitude never increasing beyond a certain limit determined by the fact that vibration energy introduced has to balance the losses of friction in the cable and the energy disappearing through the fixation points. This is the reason why the amplitude of vibrations on stranded cables never exceeds a value of approximately 80 per cent of the cable radius.

166. Internal damping of cables is a factor of great importance for the intensity of vibration. Attempts have been made to effectuate the idea of removing vibrations in statu nascendi, e.g. the Preiswerk's anti-vibration conductor. As readers will know, this consists of a core cable situated inside a hollow cable and where the core diameter is smaller than the internal diameter of the hollow cable. The core cable and the hollow cable are mounted with different specific tensions. Theoretically the oscillations in the two cables should then cancel one another out 12 . The question is whether or not such a conductor presents an internal damping much better than ordinary conductors. I think that, as the two cables of this special conductor are in contact when strung in a span, different propagation velocities for the transverse impulses along the cables cannot be reckoned with. Any additional damping is more likely due to gliding friction between the core and the hollow cable rather than one knocking against the other. In this respect the Preiswerk's conductor to some extent may be favourable compared with classic type conductors.

ooOoo



,Modulus of flexibility versus radius of
curvature at different cable stresses.
(ACSR 228 mm^2).
Module de flexibilité porté sur le rayon
de courbure à différentes tensions de câble.
(Aluminium - Acier 228 mm^2).

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TABLE I

	Predominant factors involved in vibration problems	Notion Vibration intensity	 Endurance capability
D	Diameter of cable	x pos (1)	
σ	Specific tensile stress of cable	x pos (1)	
γ	Specific weight of cable material	x neg (1)	
L	Span length	x pos (1)	
δ	Logarithmic decrement of the cable (due to internal friction in cable when exposed to flexion)	x neg (1)	
S_f	Damping efficiency of fixation device	neg (1)	
C_f	Clamp factor (purity of reflection)	pos (1)	
C_t	Terrain factor (ranging from 1.0-0.0)	pos (1)	
U	Rigidity of cable	x neg (?)	x pos
η	Transmission factor of fixation devices	x neg (negl.)	
O_c	Surface of cable: * Smoothe : Constant $O_c = 1.0$ fine strands : " $O_c = 0.4$ coarse strands: " $O_c = 0.3$	x pos (?)	
O_{str}	Surface of strands: Smoothe : Constant $O_{str.} = 1.0$ Corroded : " $O_{str.} < 1.0$		x pos
$\frac{\sigma}{\sigma_u}$	Specific tensile stress in relation to ultimate tensile strength of cable		x neg
$\frac{\sigma_{end}}{\sigma_u}$	Specific endurance limit in relation to ultimate tensile strength of cable		x pos
σ_{creep}	Specific creep limit		x pos (?) (negl.)
ν	Articulation factor of fixation device: Knife edge pivoted dead end: $\nu = 1.0$ " " " suspension: $\nu = 0.5$ Rigid fixation: $\nu = 0$		x pos
β	Angle of entry		x neg
Fc	Clamping force of cable fixation		x neg

x means that the characteristic factor in question influences the notion.

pos and neg means that the influence on the notion is positive respectively negative with increasing value of the factor.

Figures in brackets indicate the power of the factor in the empirical formulas which represent the vibration energy input from the air-stream.

negl. indicates that the influence of the factor is assumed to be negligible.

* See reference [8].