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Mechanical and Aerodynamic Problems Associated with Future Overhead Lines

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Mechanical and aerodynamic problems associated with future overhead lines

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[Plate 19]

Overhead lines operate under all weather conditions and, consequently, are subjected to various forms of aerodynamic excitation which can cause three types of oscillation to occur, namely aeolian vibration, subconductor oscillation and full-span galloping. The meteorological conditions, associated with each type of oscillation, are described and the attendant problems discussed. Solutions which have been developed to overcome these problems are described and the relevant research work is outlined. It will be shown how this work could affect the future designs of overhead lines at existing voltage levels. Finally, the problems associated with possible multi-subconductor u.h.v. lines are considered and the influences which these problems may have on the design of such lines discussed.

1. Introduction

By their very nature overhead lines for electrical power transmission are subjected to a wide range of weather conditions. It is these conditions which dominate the mechanical design of the lines and towers once the basic dimensions have been chosen to satisfy the electrical requirements. The task of choosing towers and foundations to withstand the static design loads can be carried out now with some confidence, and we do not propose to discuss these aspects of line design in this paper. Instead we shall restrict attention to the problems of conductor motion brought about by the weather conditions in which the lines have to operate.

The three types of oscillation which we shall consider are aeolian vibration, subspan oscillation and full span galloping. We shall attempt to describe the causes of the oscillations, the cures (in so far as these are known) and the effects that the oscillations will have on the design of future overhead lines, particularly u.h.v. lines.

2. Aeolian vibration

Aeolian vibration is the name given to oscillations caused by the more or less periodic detachment of vortices from the rear of the conductors in a cross-wind. The frequency of detachment (f) is related to the windspeed (V) and the conductor diameter (d) through the Strouhal number fd/V, which may be assumed to be equal to 0.2 for practical purposes. When the frequency coincides with a natural frequency of the line, vertical oscillations of the line are excited with amplitudes of up to a conductor diameter. The oscillations are found to be most severe on flat uninterrupted terrain and in very low wind velocities. These results indicate that the turbulence in the incident wind has a marked effect on the severity of the oscillations. In the most extreme cases fatigue failures have been found in conductor strands at points of support.

Aeolian vibration has been the subject of exhaustive study for single conductor lines, where a philosophy of living with the oscillations has been adopted. Field studies have shown that conductors whose normal, everyday tensile load is below approximately 20 % of the ultimate tensile strength of the conductors are much less prone to aeolian vibration. This requirement is therefore frequently incorporated into the line design, with some economic penalty.

In addition, vibration dampers are often fitted to the conductors near the ends of the spans to control the oscillations to acceptable limits. The most frequently used vibration damper is the Stockbridge damper which was originally developed in 1926. The precise way in which this damper works has always been shrouded in mystery; its success in controlling the oscillations has removed the need for better understanding.

A recent extensive theoretical and experimental treatment of the aeolian vibration of single conductors fitted with Stockbridge dampers has been reported by Claren & Diana (1969). They have dealt in great detail with the response of the conductor, the damper and the combined system, and have shown how the response of the system to aeolian vibration may be calculated using a digital computer. While this research is of great value in predicting the response of particular systems, it does not give an easily understandable picture of the way in which the vibration dampers act. A designer faced with an aeolian vibration problem but without access to the computer program, has little guidance on the vibration damper parameters which he needs to consider.

In an attempt to clarify this situation some work has recently been carried out by Allnutt & Rowbottom (1973) on a simple mathematical idealization of an overhead line fitted with a vibration damper. Using parameters determined experimentally from commercial Stockbridge designs they were able to calculate the logarithmic decrement associated with each natural frequency of the line over the frequency range of interest. By converting the energy input from the wind into a corresponding logarithmic increment they were able to make a simple determination of the range of frequencies over which the vibration will be damped out.

To summarize the conclusions briefly, it was found that Stockbridge dampers are effective at lower frequencies by virtue of their damping. At the higher frequencies the damping levels are insufficient to stop the oscillations, but the dampers distort the mode shapes near the end of the span to give much reduced oscillation amplitudes near the suspension point. This is achieved by an increase in the fluctuating strains at the damper location – an area where some fatigue failures have been reported in practice.

The work which has been completed in the last 10 years has greatly improved the state of knowledge about the aeolian vibration of single conductors. For future lines of this type it might be worth while to calculate the economic penalty incurred by the use of lower tensions, to see how it compares with the cost of lines at increased tensions with improved damping arrangements.

For bundled conductor lines aeolian vibration does not, in general, appear to be a major obstacle. The effects of wake interaction reducing the aerodynamic excitation, coupled with the greater damping brought about through the spacers, combine to reduce oscillation amplitudes. Problems have occurred on lines fitted with very rigid spacers, but provided that these are avoided few problems should occur. It is questionable whether or not bundled conductor lines need to be fitted with additional vibration dampers, and this is a further area where research work could help to reduce the costs of future overhead lines.

3. SUBSPAN OSCILLATION

Subspan oscillation is the name given to the oscillations which occur on bundled conductors involving motion of parts of the span, with individual subconductors moving relative to each other. The oscillations have recently been described in great detail (Rowbottom &

Aldham-Hughes 1972) so a brief description only will be presented here. The oscillations, typically at 1 Hz, are of self-exciting nature caused by the aerodynamic forces which the downstream subconductors experience in the wake of their upstream neighbours. For twin and quadruple conductor bundles the mean aerodynamic forces are fairly well known and the mechanism causing the oscillations has been explained. The oscillations are sensitive to the structural mechanics of the conductor system, to the angle of incidence which the bundle makes with the wind, and to the turbulence in the incident windstream. The oscillations are most severe at exposed sites, but have been reported from a wide range of locations.

Early field experience in England and Wales with quadruple bundles showed that their subspan oscillation behaviour could not be regarded as any simple extrapolation of the behaviour of twin bundles. Damage to spacers and conductors was experienced at exposed sites and similar experiences have been reported in other countries. Much research work on the aerodynamics of the oscillations and on the development of spacers has been completed since that time, and a lot of work is continuing; too much to be considered in this paper.

Instead we shall concentrate on two aspects of the work; the optimization of spacer performance and the assessment of conductor and spacer endurance.

(*a*) *Optimization of spacer performance*

Research into the mechanical characteristics of bundled overhead lines has concentrated on the design of spacers for two reasons. The spacers are the locations where damage caused by subspan oscillation most frequently occurs, and the oscillations are sensitive to the mechanical design of the spacers. It has been established by field trials of spacers in England and Wales that spacers with horizontal flexibility can give improved control of subspan oscillation, and this need for flexibility is now generally agreed. Given that the spacer is to be flexible it would appear reasonable to marry the flexibility to an energy dissipation process to help to reduce the oscillation amplitudes further, and this idea is inherent in several commercial spacers which are currently being used.

The design of the spacers to control subspan oscillation is essentially an optimization problem which can be specified as follows. Given a subconductor configuration, choose the masses, stiffness and damping levels of the spacers and the spacer locations along the span so as to maximize the damping levels in all the modes of oscillation capable of self-excitation under the action of the wake forces. This is a formidable task which cannot yet be undertaken, but we would like to present an example as a demonstration of the possibilities of the approach.

Consider a 180 m span of twin conductor fitted with two flexible spacers having some fixed damping. If we consider the antiphase horizontal modes of oscillation (which are of primary importance where subspan oscillation is concerned) there are two arrangements of the spacers which can be analysed simply. If the subspans are of equal length then the lowest frequency mode will have nodes at each spacer location, and the damping level will be governed primarily by the (small) damping levels of the conductors. If one spacer is moved right to the end of the span the same result will apply. Clearly when one spacer is moved between these two extreme positions keeping the other spacer fixed this mode of oscillation will not have nodes at the spacers and the damping level will vary.

A computer program to calculate the logarithmic decrement associated with the modes of oscillation of a bundled overhead line has been developed and the results from this program for this case are shown in figure 1. (In producing figure 1 it was assumed that the conductor self-damping was zero.) It can be seen from the results that even if the spacer parameters are unchanged, large improvements in the damping levels of particular modes can be obtained by the correct choice of spacer locations. Much work remains before the totally optimized spacer is produced, but it is clear that this approach should pay big dividends when it is fully developed.

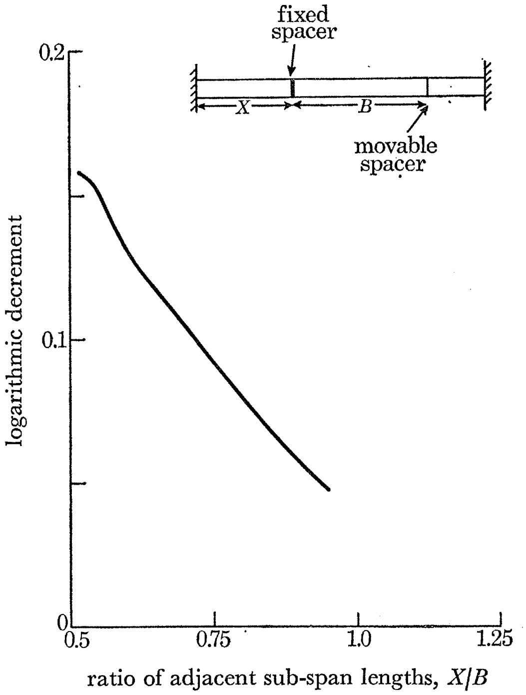

FIGURE 1. Variation of damping with relative spacer locations.

(*b*) *Assessment of conductor and spacer endurace*

We consider that this topic is of great importance for the following reason. There do not appear to be any simple panaceas available to stop subspan oscillation occurring on multi-subconductor bundles. It is not at all certain that the optimized spacer discussed above will do more than reduce the oscillation amplitudes. It is therefore essential that the conductor/spacer system is designed with the necessary endurance life, not less than the designed economic life of the conductors. In the case of subspan oscillation it is necessary to show that the conductors and spacers can withstand the induced stresses and strains for the required number of cycles. The self-exciting nature of the oscillations makes this a tricky problem because changes in the design of the spacers may change the loading which the system is called on to meet. For example, a reduction in the flexibility of the spacer to provide a greater life for the spacer may well cause the fluctuating strains in the conductors at the spacer clamps to go over their fatigue limit.

It is necessary to develop a method for predicting the modes of oscillation of an overhead line system, to determine the strains and deflexions which the various modes induce in the conductors and spacers, to determine the fatigue limits of the conductors and spacers, and to assess the number of cycles which will occur in practice in the various modes.

As a major contribution to the development of this programme a new overhead line vibration test line is being commissioned at the C.E.R.L. It has a 250 m span length, and will be able to deal with various arrangements of twin and quadruple conductors over the entire working range

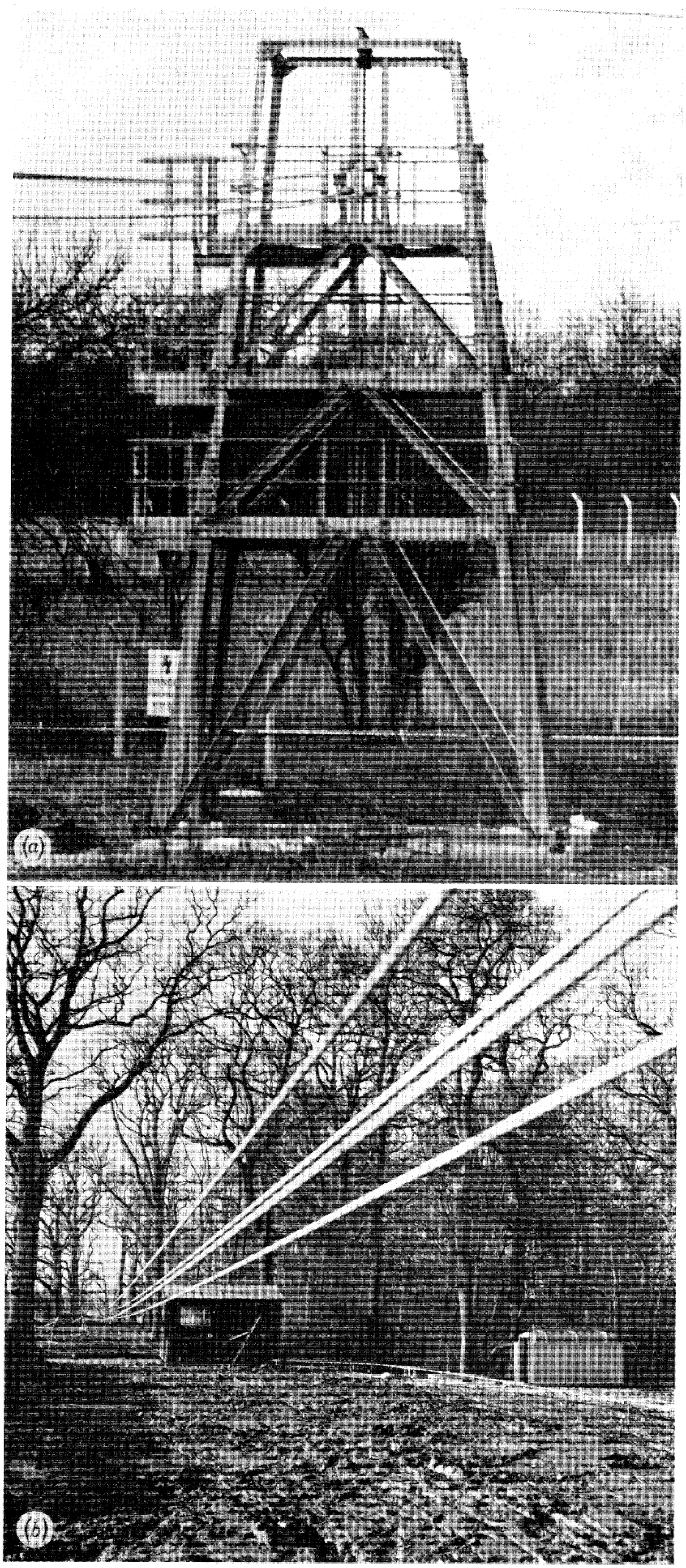

FIGURE 2. The C.E.R.L. overhead line vibration facility. (*a*) One of the terminal towers; (*b*) 250 m span with quadruple conductors.

of conductor tension. The rig has been designed to have the conductors near to ground level to facilitate ease of working (figure 2, plate 19).

With this facility it will be possible to excite the various modes of oscillation mechanically, to measure their damping levels, to measure the fluctuating strains and displacements in the conductors and spacers, and to determine the way in which all these quantities are affected by changes in spacer parameters or locations. The data collected will have the dual purpose of being used directly to assess the endurance of erected systems, and to provide checks on any theoretical predictions which may be made concerning natural frequencies and/or damping levels.

4. Full span galloping

This problem has proved the most intractable of all the overhead line vibration problems. The accretion of ice on to the conductors gives the normally aerodynamically stable conductors an unstable profile which, in crosswinds, causes the conductors to oscillate vertically with amplitudes of up to several metres in one of the lower modes of oscillation of the entire span. In addition to the mechanical wear and tear, the oscillations can give rise to phase-to-phase or phase-to-earthwire faults with consequent repercussions on the operation of the grid system and with the possibility of damage to other electrical plant. (In exceptional circumstances, e.g. the Severn crossing, galloping can occur in the absence of ice, but we do not propose to discuss these problems here.)

The oscillations are known to have occurred on all kinds of overhead lines. Bundled conductors appear to be more prone to the oscillations than single conductors. Turbulence in the incident wind and local features in terrain can have a marked effect on the occurrence of the oscillations. Until a very few years ago there were no known remedies for the control of the oscillations, but in the last few years some intensive study of the phenomena has been carried out. In what follows we shall try to outline at least some of the results which have come out of the work.

(*a*) *Aerodynamic and mechanical dampers*

Galloping oscillations commence when small amplitude oscillations start to extract energy from the airstream. They continue to grow until the aerodynamic energy dissipation from the drag of the conductors and the energy dissipation from any mechanical damping present is equal to the energy input from the lift forces. When this condition is satisfied the conductors oscillate in a limit cycle. Until recently, while net energy input versus oscillation amplitude curves were available for a number of particular aerofoil sections, no general understanding was in existence concerning the energy levels involved during the galloping of conductors, particularly bundled conductors.

Hunt & Richards (1969) produced a method for calculating the critical windspeed, that is, the minimum windspeed necessary to sustain oscillations of a given amplitude on bundled overhead lines. Subsequent work by Hunt & Rowbottom (1973) showed that the predicted windspeeds agreed well with the windspeeds prevailing at the times of galloping-induced faults on bundled overhead lines. Hunt & Richards also calculated the minimum effect that specific arrangements of perforated cylindrical aerodynamic dampers would have on the windspeeds necessary to sustain oscillations of clashing amplitude. On the basis of this work some 500 aerodynamic dampers have been erected on the C.E.G.B.'s transmission line network.

Cooke & Rowbottom (1973) extended this work to consider the effects of increased lengths of aerodynamic dampers, and to compare the relative efficiencies of mechanical and aerodynamic dampers in controlling the oscillation amplitudes. They were able to show that relatively short lengths of aerodynamic dampers (approx. 5 % of the span length) situated at mid-span were as effective, for the fundamental mode, as a structural damping with a logarithmic decrement of 0.15 – a figure which it would, in any case, be very hard to obtain with mechanical systems.

The result of all this work is a practical aerodynamic damper for use on new or existing lines. In principle almost any critical windspeed can be achieved with the dampers, but at the expense of an increased wind loading on the conductors and, hence, the towers. The effectiveness of aerodynamic dampers on existing lines will amost certainly be limited by this factor. It need not be a problem on future lines provided that the possible use of the dampers is considered at the design stage.

(b) *Use of meteorological data*

A complementary problem to the design of dampers to control galloping is the problem of knowing where to locate them to obtain the greatest benefit. Some recent work has been undertaken on this topic with some success. Few data exist on the actual location of faults along C.E.G.B. lines, but all faults are recorded, and it has proved possible to pick out from the records the faults caused by galloping of the conductors. The corresponding meteorological data have been obtained from weather recording stations as near as possible to the line. In this way a reasonable statistical picture of the faults has been built up.

It has been found that, in England at least, the distribution of wind direction at times of low temperature (< 2 °C) and moderate windspeeds (5 to 10 m/s) has very pronounced trends which agree reasonably well with the trends in the distribution of wind direction at fault times. The implication of this is that it may be possible to ascertain those parts of overhead line routes which are most vulnerable to galloping by combined inspection of the line route and the local meteorological records.

This finding goes some long way towards answering the questions concerning aerodynamic damper location. It also has considerable significance for the routing of future overhead lines for which it may be possible to minimize the risk of galloping by a suitable choice of route.

5. U.H.V. CONDUCTOR CONFIGURATIONS

The purpose of this section is to consider the effects which the oscillations described in the previous three sections will have on the conductors which have been proposed for use with u.h.v. systems (i.e. 1000 to 1500 kV). These have been basically extensions of the multi-subconductor concept to bundles of six, eight or even twelve subconductors.

It is fairly clear that, provided some little care is taken with the design of the spacers to allow for some movements in the vertical direction, aeolian vibration is unlikely to be a problem with the conductors. Subspan oscillation, however, certainly appears to be the form of oscillation which is most likely to give rise to problems on u.h.v. lines. With bundles of six or more subconductors it is virtually impossible to avoid the existence of a pair of subconductors with little vertical separation and with a horizontal separation close enough to give rise to oscillations. As a rule of thumb, with quadruple conductors sixteen to eighteen diameters is the minimum horizontal separation that is acceptable on exposed sites. The u.h.v. designs published to date (e.g. Paris *et al.* 1972) infringe this limit with designs giving ratios as small as 11.8.

Research into the oscillations is of course continuing, and improved methods for the control of subspan oscillation may well be developed (see § 3a). All that can be said at this stage is that the problem should be carefully considered before any firm design proposals are drawn up.

The situation with full span galloping is rather similar. If use is made of the best information at present available it may be possible to choose the line route to minimize the exposure to galloping. Nevertheless, if a substantial length of line is proposed over varied terrain then the possibility of galloping will still exist, and the use of aerodynamic dampers should be considered when drawing up the tower designs.

6. An aerodynamically sound u.h.v. conductor

In the previous section we have tried to point out the difficulties associated with the wind induced oscillations of conductors for u.h.v. lines based on an extrapolation of the multi-subconductor bundle. While the effect may be minimized by the application of the results obtained from the research described earlier in this paper, the problems are still being built into the lines by the basic choice of the conductor design. It might well pay, before continuing the extrapolation to bundles of six or more subconductors, to consider the design of the conductors afresh. There are obviously many problem areas to be considered, but we would like to propose that the conductor shown in figure 3 should be considered for use at u.h.v.

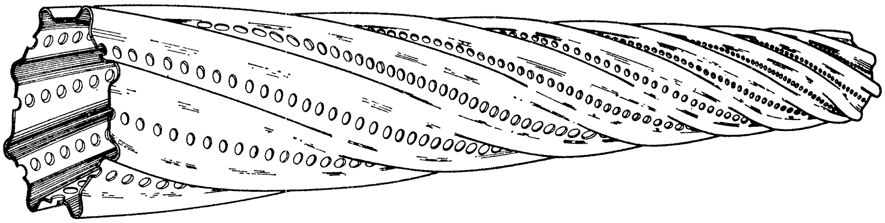

Figure 3. Proposed u.h.v. conductor.

The design is a perforated aluminium tube with multi-start helical bulges supported, if necessary, by a separate steel, glass fibre, or carbon fibre cord. This conductor is of a sound aerodynamic design. It cannot shed vortices because of its perforated nature, thereby eliminating the source of aeolian vibration. Its structure is such that subspan oscillation is quite impossible, and its aerodynamic damping properties will be sufficiently great to reduce any full span galloping oscillations to insignificantly small amplitudes.

This design is the logical outcome of the work on the elimination of conductor oscillation, and it has many desirable features in this context. It is appreciated that consideration of the electrical parameters of the line or line construction requirements may well rule out its adoption. Nevertheless, in our opinion its advantages in the control of aerodynamically induced oscillations merit its serious consideration as a future u.h.v. conductor.

This work was carried out at the Central Electricity Research Laboratories and this paper is published by permission of the Central Electricity Generating Board.

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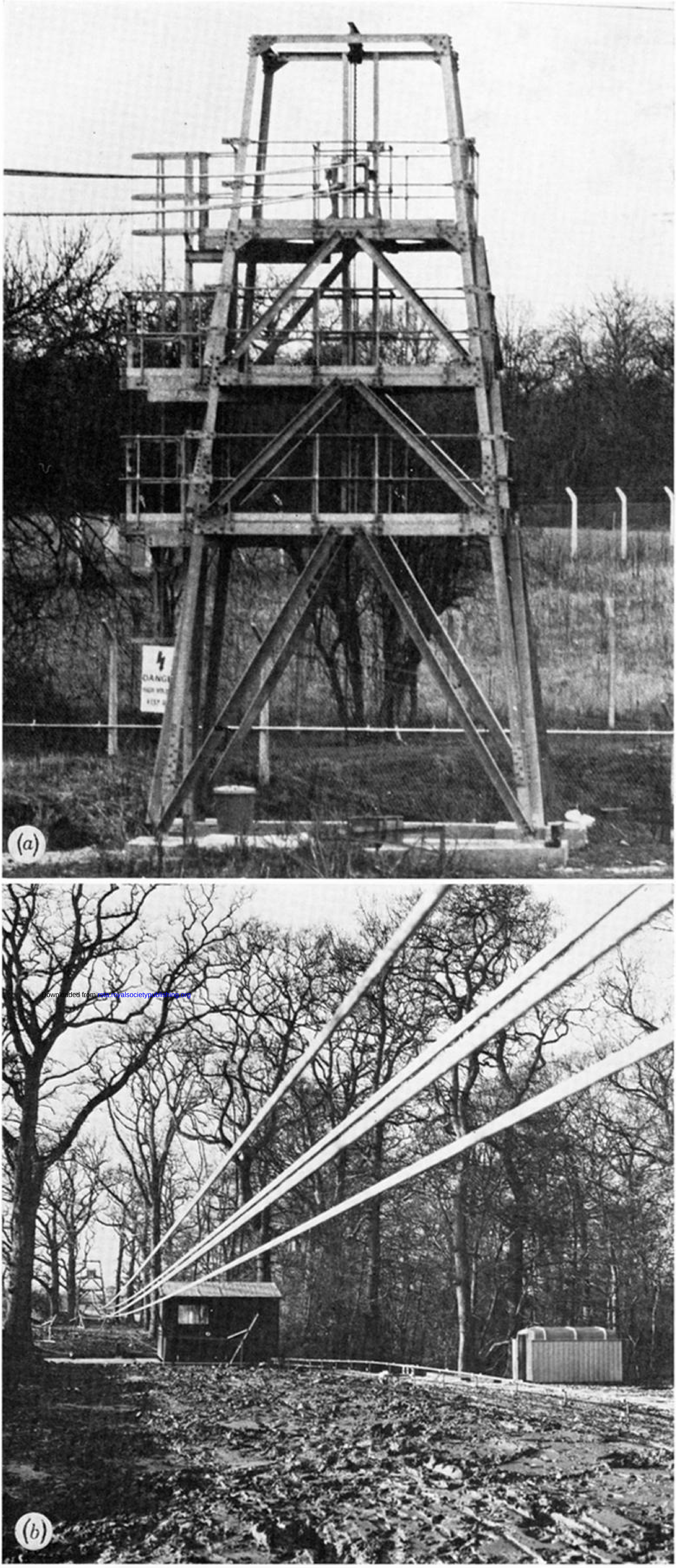

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