# Conference on Galloping Conductors, held at the Laboratories of the National Research Council of Canada, November 22 and 23, 1948

National Research Council of Canada. Radio and Electrical Engineering Division

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LABORATORIES

OF

THE NATIONAL RESEARCH COUNCIL OF CANADA

RADIO AND ELECTRICAL ENGINEERING DIVISION



# CONFERENCE ON GALLOPING CONDUCTORS

HELD AT THE LABORATORIES

OF THE NATIONAL RESEARCH COUNCIL OF CANADA

NOVEMBER 22 AND 23, 1948

OTTAWA

JULY, 1949

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# CONFERENCE ON GALLOPING CONDUCTORS

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Ottawa,
July, 1949.

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## CONFERENCE ON GALLOPING CONDUCTORS

I

### INTRODUCTION

On November 22nd and 23rd, 1948, a conference on galloping conductors was held at Ottawa, in the Laboratories of the National Research Council of Canada. Delegates from public utility companies and research laboratories in both Canada and the United States attended. This conference was the largest and, perhaps, the most important, of a number held in Toronto, Chicago and other cities, on galloping conductors, and it is believed that a record of the proceedings would be of considerable interest, particularly to those working on this problem in other parts of the world. The proceedings of the conference were reviewed at a later meeting held in New York City on January 31st, 1949, and views expressed at that meeting are also included.

In presenting this report, no attempt has been made to condense or revise the minutes of the conference, except that the material has been rearranged topically to facilitate its use as a reference on the subject.

..... ..... .....

The following delegates attended the Ottawa conference:

| | |
|---|---|
| T.J. Burgess | |
| A.E. Davison | |
| W.P. Dobson | |
| A.T. Edwards | |
| A.D. Hogg | |
| H.J. Muehleman | |
| H.C. Ross | |
| J.W. Speight | |
| J.H. Waghorne | |
| R.B. Young | - All of Hydro-Electric Power Commission of Ontario |
| C. Becker | Public Service Co. of Northern Illinois, Chicago |
| G.E. Dean | Public Service Electric and Gas Co., (Newark, N.J.) |
| J.P. Den Hartog | Massachusetts Institute of Technology, Cambridge, Mass. |
| R.T. Henry | Buffalo-Niagara Electric Corporation, Buffalo, N.Y. |

| | |
|---|---|
| H.C. Moorecroft | Pennsylvania Water and Power Company |
| M.S. Oldacre | Utilities Research Commission, Chicago, Ill. |
| A.S. Runciman | Shawinigan Water and Power Company |

B.G. Ballard
W.F. Campbell
F. Cheers
W.J. Cox
F.C. Creed
A.H. Hall
N.L. Kusters
C.D. Niven
G.E. Rickwood
R.J. Templin
E.S. Turner
J.P. Uffen - All of The National Research Council of Canada.

## II

## RECENT EXPERIENCES OF PUBLIC UTILITY COMPANIES

### Reports and Corrective Measures Taken

Mr. Dean, of the Public Service Electric and Gas Company (of New Jersey) said that his company had tried increasing both the vertical and horizontal spacings between conductors to prevent them from touching. These lines, which are for transmission at 132 kilovolts, are all 500,000 CM copper with 800-900 foot spans or 795 ACSR 30% equivalent, and have a 13-foot vertical separation. They had tried increasing the vertical separation from 13 feet to 19 feet and increasing the horizontal displacement of the centre conductors from 3 feet to 6 feet. The phase-to-phase separation was increased, but the phase-to-ground separation was not. On January 1st, 1948, the lines galloped at night time, and they were unable to make observations. On a new line which they are putting up, they are compromising and using about 16-foot vertical separation instead of the 19-foot separation which they had tried, for reasons of economy.

Mr. Runciman, of the Shawinigan Water and Power Company, mentioned three cases of trouble during March, 1948. One of these was on 700-foot spans strung on 195-foot towers, when the wind reached velocities of the order of 35-45 mph. The galloping in this case was caused by an ice formation which was in the form of a tail, $2\frac{1}{2}$ inches long, with a maximum vertical dimension of $1\frac{1}{2}$ inches. This was on a 3/0 ACSR conductor. The amplitude of galloping was 17 feet, 12 feet above the normal and 5 feet below it, and all wires were brought down.

This happened during a week end when the load was light. The second and third cases he cited were on lines having spans of 219 feet and 166 feet, on both of which a 10-foot gallop was observed. This gallop was 5 feet above and 5 feet below the normal position. In these last two cases no material damage was sustained.

He then mentioned the case they had encountered at Thetford Mines some years ago. Since the first trouble there, they have had to return twice to similar locations. The remedy in this case was discovered by luck; the spans were 300 feet long and were composed of six units in suspension, the lines were 60-kv lines made up of 267,800 CM ACSR conductors. A man was sent up to attach a rope to the wire and pull it in to the tower. As soon as the rope was thrown around the wire and the wire pulled in towards the tower, galloping ceased. Since then, strings of insulators have been used to duplicate this effect and, so far, there has been no repetition of these cases. He then pointed out that while they could not afford to do this over their entire system, they could do it on spans where experience has shown that galloping is likely to occur.

Mr. Oldacre, of the Utilities Research Commission (of Chicago) reported that about a year ago a report form was sent to all members of the EEI T and D Committee, and to representatives of some other companies, asking for as much detailed information as possible on any cases of galloping that were observed. About two dozen reports were received, with the information in a widely varying degree of completeness, and it seemed impossible to draw any conclusions from the data submitted. The difficulty of making adequate field observations is well realized, and accounted for the inability to obtain complete information about most cases of galloping. The data will be tabulated and made available to all those interested, for their own analysis of any particular phase of the problem.

Lines Equipped with "Aeolian" Dampers

In reply to a question, Mr. Muehlman said that he did not know of any benefit his company had derived in the damping of galloping from the use of their T and B dampers, but pointed out that galloping is a very infrequent occurrence. While they have had no galloping with single-circuit 220, and he did not know of any galloping having occurred with 110 and 220 equipped with Tebo dampers, he did not feel that these dampers were capable of contributing at all to the suppression of galloping. He did not feel sure that it would be economically feasible to use dampers to suppress galloping, in the event that satisfactory dampers could be devised.

In summarizing, Mr. Runciman said that people who have these dampers on their line do not seem to have any trouble with galloping, at which point Mr. Dean remarked that they have had galloping on lines equipped with Stockbridge dampers. Mr. Runciman amended his statement to include only the Tebo type and pointed out that these torsional dampers used a short arm, and since no galloping had been observed on lines equipped with them, short arms might be feasible for the suppression of galloping.

Dr. Den Hartog suggested that it might be possible to utilize the torsional strength of the line for damping, by placing the arms on alternate sides at 30 to 40 foot intervals. He pointed out that information is sorely needed on how much force is required, and for how long, in order to start galloping. He also would like to know what is the internal damping in stranded cable.

Mr. Speight remarked that in the case of aeolian vibration, his company relied on the internal friction of HH copper to damp out the vibration, but in the case of ACSR they could not rely on internal friction and had to use torsional dampers. He said that the Ontario Hydro have a line across the Ottawa equipped with torsional dampers, and while they have no faith in these dampers from the point of view of suppressing galloping, they have no information as to whether or not these dampers would have any effect.

Regarding the line mentioned by Mr. Speight, Mr. Burgess stated that it was a long span having two circuits on the same towers, and that serious trouble had been experienced there a few years ago. At that time, it was noticed that the only line on which no trouble occurred was the line equipped with Stockbridge dampers. This was discussed with Mr. Tebo, and Mr. Tebo felt the same as Mr. Speight, namely, that torsional dampers would not be of any use. However, four dampers were put on each end of each conductor spaced at 6, 12, 18 and 24 feet from the point of suspension, and since that time they have had no trouble at this location, but he pointed out that he did not think that this meant very much.

Another place where trouble has been experienced was at Hamilton Bay. This was also cleared up by using torsional dampers, but in this case the dampers were not used as extensively as in the case previously mentioned. At Hamilton Bay they also increased the spacing as well as putting in the dampers. During this coming winter they would record the movement at both these points.

Mr. Speight said that in his opinion, the dampers referred to will not work from an energy absorbing point of view, but they may work in the initial case and prevent galloping from starting, by throwing the oscillation out of phase.

Mr. Runciman suggested that T and B dampers might be tried out in the Gary installation. This would have to be a co-operative effort since the dampers would have to be sent over from this side of the border, because they are not manufactured in the United States.

## De-Icing Practices

Mr. Henry stated that probably his firm's most severe case of galloping had occurred two or three years ago, the day following Christmas, when 8 out of 20, 150-kv circuits failed. He then cited another case of galloping involving a 500,000 CM copper line, in which one conductor was broken and much of the hardware was either broken or unhooked.

Up to the present time they had endeavoured to counteract galloping by increasing the current to melt the sleet. In achieving this, two of the methods used involved taking the lines out of service. Short stretches of the order of 15 miles in length were shorted at one end and fed from auxiliary 12-kv generators. Longer lines, that is from 100 to 150 miles long, were fed from the 66-kv bus and still longer ones from the 110-kv bus. Another method they had tried was to concentrate the load on fewer lines for short periods, and, in the case of loops, to feed back around the entire loop. All of these schemes have been fairly successful and he felt that several cases of galloping had been avoided by adopting these precautions.

Regarding the subject of melting sleet, Mr. Dean said they have found this to be impractical on their lines, due to the very short lengths involved. In their case, they have lots of load and no geography, and for 132-kv lines, 10 miles would be a long line. These lines are of 795 ACSR. On the 220-kv lines, 50 miles between stations would be a very long distance. The closest compromise they have been able to achieve in this case is to load the line to sleet prevention ratings rather than sleet melting. Sleet prevention amperages have been given to all station operators, and they have been given instructions to load the lines to these values whenever possible when sleet storms are in the offing. To date they cannot report any progress on lines using this principle, since insufficient opportunities have arisen for thorough testing.

In discussing a recent conference at Gary, Mr. Runciman said that it had occurred to him at that time that the power or energy involved in the galloping of a transmission line might be used, in some fashion, to twist the wire, and so break off the ice formation which was causing it to gallop. He said that at that time they had had no success in sketching a suitable mechanism on the drafting board to accomplish this result. Later, however, it had occurred to him that this might be done by fastening an arm to the conductor, extending horizontally, with a weight at the end. This would be similar to a T and B damper with an extended arm. In operation, the inertia of the weight would cause a twisting of the wire when the wire attempted to move vertically in a gallop. However, this might cause additional trouble with resonance.

Mr. Becker pointed out that, while it was very easy to strip the ice from solid conductors, it was extremely difficult to strip stranded conductors.

## Velocity of Wind

Mr. Henry said that moderate winds around 10 to 15 mph caused the most trouble in galloping. He stated that his company did not expect galloping when the wind reached 30 mph. Mr. Muehleman stated that steady winds are the principle cause of galloping; high winds did not cause as much trouble as moderate winds, but they have had cases of galloping at high winds. He also pointed out that high winds and sleet very rarely occur at the same time. Mr. Henry then said that he did not mean that galloping would never occur at high winds, but that it rarely did, and it was in the case of moderate winds that they were most troubled by this phenomenon. Mr. Runciman stated that their records showed galloping when the winds were of 30, 35 and 45 mph velocities, but he thought that these figures were taken after the sleet had formed and the galloping had started, and from his own experience he felt that the lower velocities actually caused the most trouble, say around 20 mph.

## Galloping in the Absence of Icing

Mr. Oldacre stated in his report that there seems to be considerable acceptance of the explanation of galloping proposed by Dr. Den Hartog, at least for the more common cases with ice on the conductor. If it were possible to authenticate cases of galloping of round conductors without ice, this would be taken as conclusive evidence that galloping could occur under other conditions than covered by Den Hartog's theory. It is possible that other factors, outside of Den Hartog's theory, may have some influence on the motion of the conductor. There have been fairly frequent reports of galloping without ice, but it is practically impossible to substantiate such reports. Within the past week, information had been received from Mr. A.F. Sedgwick, Electrical Engineer of the United Illuminating Company at New Haven, that he had witnessed three such cases. One case was this year, and the other two were in 1934 and 1935. The lines were apparently of ordinary wood pole construction for relatively low-voltage service. In one case, the galloping was at a maximum amplitude of plus or minus 12 inches at a point about 30 feet from the pole, and the galloping was in a vertical plane. In another case, the galloping was about 36 inches in maximum amplitude at a point about 40 feet from the pole, and the galloping was in a horizontal plane. Part of the span in this case was a tree wire with heavy insulation. This particular case was on a 6200-volt line where the wire spacing was 28 inches. The wires shorted one another several times in one span. The third case had 6-inch galloping in a vertical plane. In all cases the wind was quite strong, 30 mph or more*.

In all of the cases of galloping without ice which he had mentioned, the wind was in excess of 30 mph, and Mr. Runciman pointed out that in this case the forces would be of the order of 500 to 1,000 pounds and the vertical component would then be an appreciable force even though it is only a small component.

Mr. Henry discussed experiences with galloping on lines when no sleet or ice was present. He stated that while he had no data on this type of galloping he had himself observed it even in the summer time, but he believed that it occurred only when the wind direction was not normal to the transmission line. He pointed out that in this case the wind would be blowing across the strands on one side and along the strands on the other, thereby creating the same sort of aerodynamic asymmetry which occurs on an ice-laden conductor. He felt, however, that such cases of galloping occurred rarely, and with such low intensity that they need not cause concern, and he expressed the view that if galloping resulting from sleet formation could be eliminated, the major part of their problem would be solved.

## III

## RECENT FIELD TESTS

### Tests by the Chicago Group - Damping Arrangements**

The study of the galloping conductor problem by the Chicago group has been directed along two lines: First, experimental study on the test lines of the Public Service Company of Northern Illinois at Maywood to determine if some means could be devised for minimizing the effects of galloping. Second, a study to develop an acceptable theoretical explanation of galloping. This would be of value for the design of new lines and development of mitigating devices for existing lines. Some of the theoretical study is being done at one of the universities. Recent work has included an analysis of the motion of a conductor as shown by moving pictures.

* This paragraph is an extract from the review prepared by Mr. Oldacre and distributed to delegates at the conference.

** An extract from the review prepared by Mr. Oldacre and distributed to delegates at the conference.

The test line at Maywood has been moved to a new location that is not as favourable for galloping as the previous one, and the occurrence of galloping was considerably reduced. The half-round airfoils on the two conductors have been rearranged so that one is affected by northerly winds and the other by southerly winds, thus giving a little greater period of observation.

The test line consists of four spans, each 250 feet long, carried on wood poles. There is a dead end at each end of the test line and links are used on the three intermediate poles to represent suspension insulators.

Several arrangements using Houdaille lever arm automobile shock absorbers as dampers have successfully stopped the conductor motion. The arrangements were rather complicated as the shock absorbers were mounted so that the connection from the arm of the absorber to the conductor was about ten feet from the insulators. Some tests were made to measure the energy absorption ability of these shock absorbers and thus determine the energy absorption required to stop galloping. These tests have not been carried far enough to give any definite data.

Another damping arrangement, consisting of a tie from the conductor on one side of the suspension insulator to the conductor on the other side of the suspension insulator was tried on the basis that interference would occur between the galloping of adjacent spans and the effect would be minimized. One type of tie was made with a piece of conductor ten feet to fifteen feet long, which was clamped to the line conductor by ordinary suspension clamps. The tie was under some tension but not enough to change the sag of the main conductor any appreciable amount. The arrangement was effective in suppressing about two-thirds of the galloping on the main conductor. This arrangement has not been explored over the full range of possibilities. Installation of energy absorbing devices in a tie connection has been discussed, but no definite data has yet been obtained. The method of attaching the cross-tie to the line conductor is open to question if trouble at the point of attachment is to be avoided.

It is realized that the cross-tie below the insulators, as described above, does not comply with some of the theoretical conclusions that have been stated, but the reduction in galloping seems to warrant further study.

Spring-Loaded Weight Dampers

Mr. Dean stated that they had forced their test line into oscillation by springing one of the dead ends. This line was a 795 ACSR on wood poles, with an 800-foot span, and the stringing tension was

3,080 pounds. By means of gear trains, galloping was obtained at frequencies of 20, 60, 120 and 180 CPM, the 60 CPM giving 5 complete loops and the 120 giving 10 loops. They found that this method of changing the span length did not give the best results in all cases, but by interposing a bridle arrangement between the lines and the springing arrangement, they were able, in some cases, to get more definite establishment of the different loops than they could by shaking the pole.

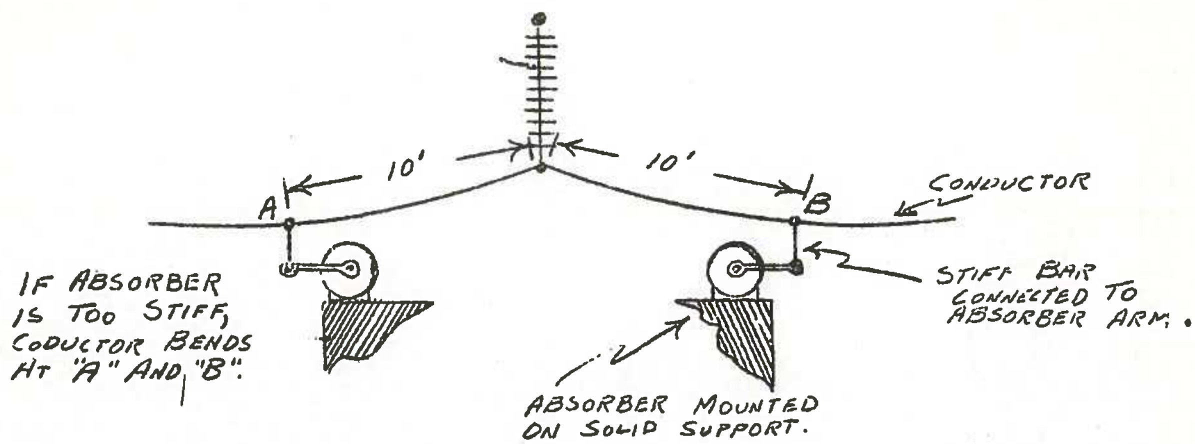
This test set-up was used to test the efficacy of spring-loaded weight dampers. These were encased in a steel pipe and attached to the conductor, the weight being supported by the spring. The dampers, which had been adjusted for 180 cycles, worked satisfactorily at 180 and also 120 cycles, but were very poor at 60 and 20 cycles; at 60 cycles they even tended to intensify galloping. The frequency of galloping for this span normally is somewhere between 20 and 40 cycles. They took photographs showing the operation with the dampers in place, but as yet these have not been analyzed, due to lack of time and personnel, but the data is all recorded.

He pointed out that one fault with this type of test is that too much energy is being fed into the line in comparison with that which would be fed in by the wind. This is evidenced by the fact that the galloping increased at a much higher rate than has ever been experienced in natural cases. In addition, after the galloping had been started, they continued to feed in much more energy than the wind would do. When the test set-up was shut down, and V-shaped mouldings put on the conductors, they were not able to get the line to gallop. Unfortunately, work on this project has been subject to many interruptions, including the design and erection of the new line with increased vertical separation, but they are now ready to resume work on this problem. Up to the present they have found that the dampers which have been tried are not practical, due to the large amount of noise which is associated with their operation.

<u>Other Damping Devices Tested</u>

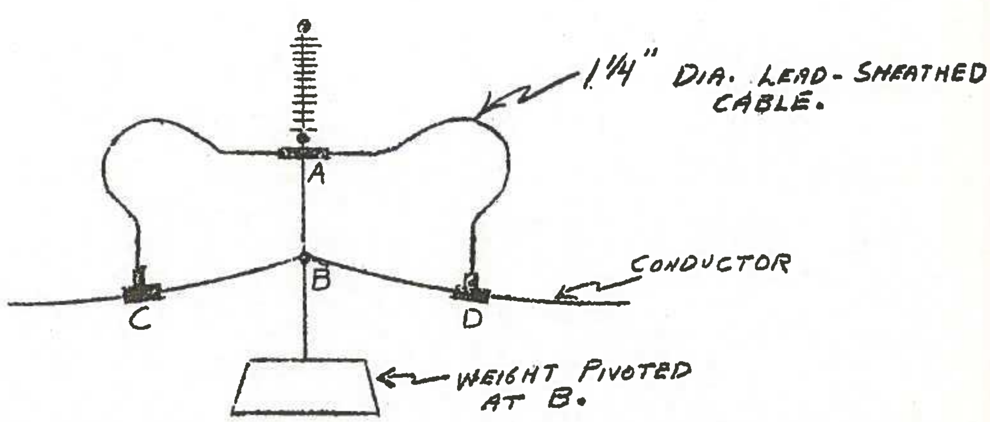
Mr. Becker showed two films of galloping, on both test and actual lines. He mentioned that the start of galloping on the test line appears to take two or more different forms: (a) The previously quiet conductor begins to "quiver" - that is, the span begins to vibrate in, say, 10 to 20 loops, with an amplitude of only a small fraction of an inch. Then, after about 1 to 5 minutes, with suitable wind conditions, the number of loops rapidly decreases to 4, 3, 2 or 1 loop; (b) The previously quiet conductor seems to go directly into the 4, 3, 2 or 1 loop gallop. No movie record has been obtained of either of these apparently different types of initiation. The latter type has been seen much more frequently than the former.

The movies showed the results obtained with the following methods of damping.




STANDARD FORD HYDRAULIC SHOCK ABSORBERS.

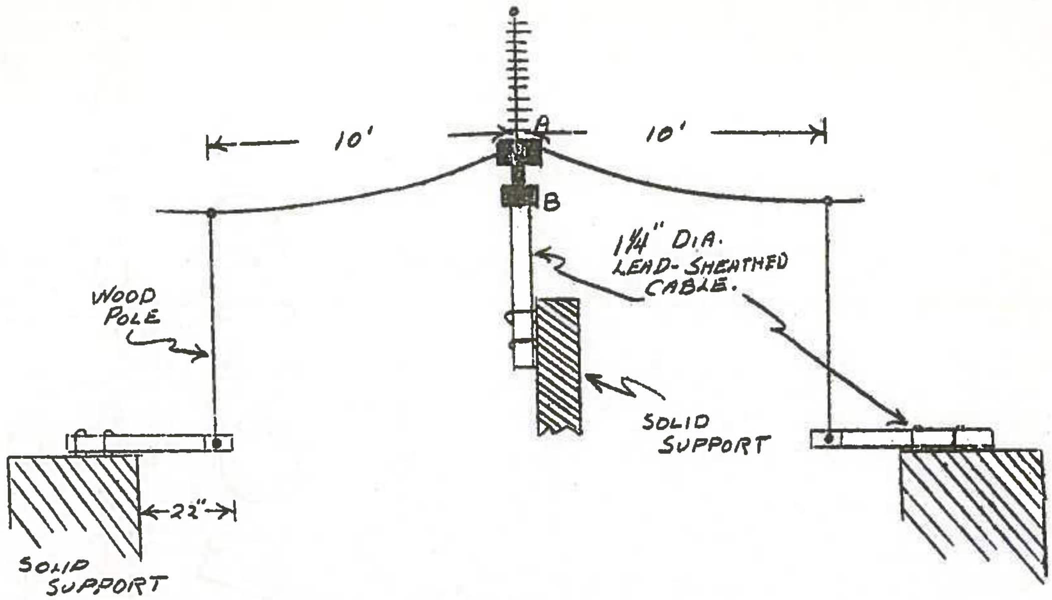
FIGURE 1.




AB = 12"
BD = 22"
AB = STIFF BAR CONNECTING BOTTOM OF INSULATOR STRING TO CONDUCTOR CLAMP.
LEAD CABLE IS FASTENED SECURELY AT A, C AND D.

THE WEIGHT APPEARED TO BE NECESSARY TO PREVENT PIVOTING AT A.

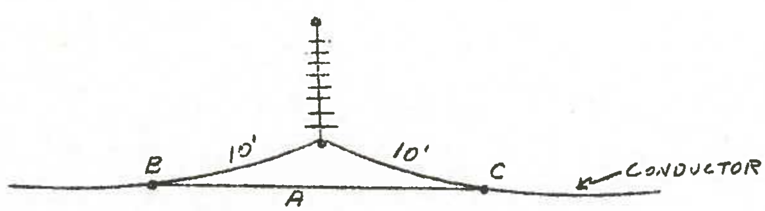
FIGURE 2




AB = STIFF ARM CONNECTING CONDUCTOR CLAMP TO UPRIGHT LEAD CABLE.

FIGURE 3

VERTICAL LEAD CABLE DAMPS THE ONE-LOOP GALLOP. HORIZONTAL DAMPS THE MULTIPLE LOOPS AND CONSIDERABLE OF THE ONE-LOOP GALLOP.




"A" IS A WIRE CROSS-TIE PULLED TIGHT ENOUGH TO BEND THE CONDUCTOR AT "B" AND "C". TENSION DATA NOT YET AVAILABLE.

FIGURE 4

IN THE TEST SHOWN IN THE MOVIES, THIS METHOD INDICATED A REDUCTION IN AMPLITUDE OF ABOUT 65% IN A WIND OF 10-12 M.P.H. (60°-70° TO THE LINE) AND UNDER THE CONDITIONS THAT EXISTED AT THAT TIME.

The method of Fig.3 was decidedly the more effective. The methods of Figs. 1 and 2 caused over 80 per cent reduction in amplitude. The degree of suppression shown in the movies for the device of Fig.4 has not always been obtained. The reason for the variable results is under study. No firm data have as yet been obtained for dampers on the test line in winds over 15 mph.

## Measurement of Tension

Mr. Moorecroft stated that the field trials carried out by the Pennsylvania Water and Power Company were on a 5-span test set-up, using 300,000 CM aluminum conductors equipped with D-section foils. This line, which runs north and south, gallops in a gusty west wind, but, unfortunately, west winds do not occur very frequently in that location. If they had to wait for natural galloping to occur before making measurements, they would get nowhere, since only two cases of galloping can be recalled since 1915.

SR-4 strain gauges were used to measure the tension in the end of the span, since experience had shown that on this line galloping occurred in two loops. Four gauges were put on at each quarter-span position and these were fastened directly to the strands. A Wheatstone bridge was used, with 800-cycle excitation, in conjunction with a magnetic oscillograph, to record the tension at the ends and the quarter-span points. The oscillograph was also used to record the vertical motion of the conductor. This was accomplished by wrapping a string around a pulley on a rheostat, and attaching the other end to the conductor. When the conductor moved in a vertical direction, the rheostat could be used to obtain a voltage proportional to the movement. This was attached at the quarter-span position, since it was believed that information on the movement of the conductor at this point was most important. In addition to the above, the oscillograph was also used to record the wind velocity and wind direction.

From the oscillograms which have been obtained, it was observed that very little change in end tension occurred when the galloping was changed by manual aid from the two-loop gallop to the fundamental gallop. However, the oscillograms showed that the tension is greater at the end when the looping is composed of the harmonic as well as the fundamental gallop. No opportunity had yet been obtained for analysis of the results, but they hoped to analyze them in the near future.

## The Vibration of Flat Conductors*

Last fall the Hydro-Electric Power Commission of Ontario approached the Division of Physics of the National Research Council for a contribution to the knowledge of galloping of transmission lines. Its Director, Dr. R.W. Boyle, called a brief conference, attended by Mr. W.P. Dobson, at which it was agreed to study for a change the vibration of flat conductors, leaving the question of the galloping of cylindrical conductors to the Aerodynamics Section. One of the reasons for this choice was that for flat conductors the wind forces can be expressed by a simple formula and the probable behaviour of the span computed beforehand, without experimental work. It is known, for instance, that when

*This paper, prepared by Dr. R. Ruedy of the National Research Council of Canada, was distributed to delegates at the conference.

a wind of velocity V blows against a flat surface at an angle $\theta$, it produces a lift

$$L = C_1 V^2 \theta$$

per unit area, where $C_1$ is a constant which has been determined by theory and experiment. It is also known that this lift is not applied along the middle line but nearer to the windward edge, at one-fourth of the width of the surface. The line of application varies only slightly with the angle of attack, whereas, for a wing-shaped cross section, its position varies with the angle. In both instances, the eccentric position of the line of attack causes rotation of the surface.

It is not to be expected that a flat conductor vibrates with a large amplitude in the absence of rotation. When the surface yields to the lifting force and moves upward at the speed $\mathring{y}$ (the dot denoting the derivative with respect to time), the wind which comes from a definite point has to catch up with the surface and is therefore delayed an equal distance $\mathring{y}$ in the opposite direction. Consequently, it seems to blow at a smaller angle than if the surface were at rest.

The difference is greater the more rapid the motion of the flat surface. In short, the vibration of a flat conductor may be self-excited but it is also self-damping, and large amplitudes are difficult to obtain.

Conditions change completely when the flat surface rotates about its longitudinal axis in such a way that a large angle of attack is maintained between the wind and the surface. The motion would be a combination of transverse vibration and a simultaneous rotation at the same frequency but with a different phase. Where the speed is highest, the inclination should be greatest.

As far as the theoretical study of such a motion is concerned, it is merely necessary to use the equation of motion for the stretched string

$$\underset{\text{(inertia)}}{m\ddot{y}} + \underset{\text{(friction)}}{C_y\mathring{y}} = \underset{\text{(tension)}}{T\frac{\partial^2 y}{\partial x^2}}$$

and to add the external force exerted by the wind with the correction for the angle of attack.

$$\underset{\text{(lift)}}{C_1 V^2 (\theta - \frac{\mathring{y}}{V})}$$

A similar equation holds for the rotation except that the moment of inertia has to be used in place of the mass:

$$I\ddot{\theta} + C_o\mathring{\theta} - T'\frac{\partial^2 \theta}{\partial x^2} = C_2 V^2 (\theta - \frac{\mathring{y}}{V})$$

A simple solution of these equations fulfilling the condition that the ends remain at rest and that rotation and transverse vibration have the same frequency is

$$y = A \sin \frac{n\pi x}{L} \sin w\, t$$

$$\theta = B \sin \frac{n\pi x}{L} \sin (w\, t + \phi),$$

where y is the motion in the direction at right angles to the length L of the string, θ the angle of rotation about x, A the amplitude of transverse motion, B the greatest angle of rotation at the given point, w the circular frequency assumed to be the same for transverse and torsional motion, ∅ the phase angle, and n any whole number, most frequently = 1, for the fundamental.

There are four unknown quantities, A, B, w and ∅ but only two equations. A third equation can be obtained from the simultaneous presence of sin and cos terms so that three of the quantities mentioned can be determined, for instance the ratio A/B of the amplitudes, the frequency w = 6.28f, and the phase angle.

In order to determine A/B it is merely necessary to go with y into the expression for $\ddot{y}$. It is found that

$$\frac{A}{B} = \frac{C_1 V^2}{\sqrt{(w_T{}^2 - w^2)^2 m^x + (C_y + C_1 V)^2 w^2}}$$

If y is introduced also into the equation of motion for the rotation, a rather complicated expression for the common frequency is obtained.

$$w^2 = \frac{(C_y + C_1 V)\,(T' n^2\pi^2/L^2 - C_2 V^2) + C_o T n^2\pi^2/L^2 + C_1 C_2 V^3}{I(C_y + C_1 V) + mC_o}$$

The calculations indicate that when the amplitude of rotation in B is zero, the transverse amplitude also is zero but that large transverse amplitudes are possible when at least approximately

$$w = w_T$$

at this frequency

$$\frac{A}{B} = \frac{C_1}{(C_y + C_1 V)} \; \frac{V^2}{w}$$

When for the same maximum angle of rotation B the wind speed is doubled, the amplitude is quadrupled; when the frequency is reduced from 30 per sec. to 1 per sec., the transverse amplitude is multiplied by 30.

Large amplitudes are possible without rotation only when $C_y + C_1 V = 0$. Surfaces for which this equation is satisfied remain to be found; for plane surfaces both Cy and $C_1$ are positive.

When it became possible to engage students for summer work, Dr. Boyle suggested that tests be made by Mr. F.R. Riddell. It was planned at first to string long flat metal bands across the flat roof of the building, but this location had to be given up. Dr. C.D. Niven then gave permission to use a small wind tunnel. The length that could be accommodated was only about 9 in., and in order to obtain vibrations that could be studied with the available equipment, elastic bands had to be strung between the supports in place of metal conductors. Some tests with bands twice as long could be carried out in a model built for one of the large wind tunnels, made available by Mr. W.F. Campbell so that the possible influence of turbulence could be ascertained. It was found to be negligible.

The results of Mr. Riddell's work are briefly as follows:

(a) As regards frequency, the comparison between computed and measured values is given in the following list taken from a longer table in the complete report.

| Tension lb. | Wind Speed m.p.h. | Frequency c.per sec. Calculated | Frequency c.per sec. Observed | Amplitudes A Calculated | Amplitudes A Observed |
|---|---|---|---|---|---|
| 1/2 lb. | 6.4 | 31 | 31 | 0.15 | - |
| 1/2 lb. | 7.8 | 32 | 31 | 0.5 | 1.2 |
| 3/4 lb. | 7.8 | 40 | 40 | 0.2 | 0.6 |
| 3/4 lb. | 8.8 | 41 | 40 | 0.5 | 1.2 |
| 1 lb. | 9.9 | 45 | 45 | 0.2 | 0.6 |
| 1 lb. | 13.1 | 45 | 45 | 0.4 | 0.6 |

The calculated and the observed frequencies agree.

(b) The amplitudes A computed for the observed rotations B agree fairly well with the observed amplitudes given in the comparison in cm. These were obtained from direct observations instead of from photographs and may have been overestimated. According to the formula, the amplitude would be about 1/2 in. at 20 miles per hour and from 15 to 20 in. at frequencies of about 1 cycle per sec.

(c) The observed difference in phase was always close to 90°. Theoretically, the phase difference is exactly 90° only when

$$w^2 = \frac{n^2\pi^2}{L^2} \cdot \frac{T}{M}$$

The adjustment of the wind speed in the tunnels was not sufficiently fine to obtain complete equality, but w and wT usually agreed to within a few cycles.

The agreement between theory and experiment shows that it would not be fanciful to look for possible rotation of the conductors when galloping occurs. The amount need not be large, only about 40° for a whole span and, therefore, less than 1° per foot near the ends. Rotation is considered in the very early reports, for instance, by Mr. A.E. Davison at a time when galloping was still called dancing. There still remains, however, the question as to whether glaze deposit can transform round conductors into flat shapes. The available studies indicate that in the early stages of glazing, lens or wing shapes are the rule. This is shown by photographs.

The possible presence of rotation will have to be considered when the question of the prevention of galloping arises. If it plays a part in galloping, the simplest remedy would be to destroy the agreement between transverse and rotational frequencies. Several methods can be used, but there are other cures. Because, in general, only a few spans vibrate violently, reduction in amplitude can be obtained by letting the galloping spans set other spans in motion and dissipate the surplus of energy. This means the use of light clamps. In the few locations where galloping is an almost yearly occurrence, it may be necessary to adopt swinging arms for supporting insulators and conductors. The insulator strings are attached to a horizontal beam which is supported by an inclined shaft that can turn about its long axis. The method is described in an article by Parodi and Queunie, a translation of which can be made available.

For lack of a wind tunnel, the vibration of a short flat band in the air current from a fan is shown. When intermittent illumination is suitably timed, the strip is visible only during a fraction of the cycle; the change in the angle shows the presence of rotation, and the setting of the stroboscope gives the approximate frequency.

## IV

## THEORETICAL DISCUSSIONS

### The Rebound of Conductors*

(A review and expansion of Hunziker's theory)

If the rebound were a slow motion, it would be equal to the difference between the sag $f_1$ in the ice- or snow-coated condition and the sag $f_o$ of the span after the loss of the coating, that is,

$$y = f_1 - f_o$$

where the sag f for a span of length a is given by the formula

$$f = \frac{a^2 j}{8p}$$

p being the tensile stress at midlength, and j the weight per unit length reduced to unit metallic cross-section.

If the tension $p_o$ in the span without the full snow or ice load is known, the tension $p_1$ produced when the weight j of cable and overload per unit length and unit metallic cross-section is found from the equation of the catenary coated with ice or snow, or from the approximate equation,

$$p_1 - p_o = \frac{a^2 E}{24} \left( \frac{j_1^2}{p_1^2} - \frac{j_o^2}{p_o^2} \right)$$

where E is Young's modulus of elasticity and the subscript 1 refers to the condition where a given overload has to be carried. It is then only necessary to introduce $p_1$ and $j_1$ into the equation for $f_1$ and to calculate the sag and the difference $f_1 - f_o$.

(a) However, if the coating of ice drops suddenly, the acceleration acquired by the rebounding conductor decreases its weight in the ratio

$$j_a = j_o \frac{g + \ddot{y}}{g}$$

where $j_o$ refers to the condition without overload, $\ddot{y}$ is the upward acceleration, and g the acceleration due to gravity. The weight is variable during the rebound and must be introduced into the formula for $f_1 - f_o$ giving the height of the rebound. In practice the difference $y = 2(f_1 - f_o)$ is often used instead, but the result is not much more

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* This paper, prepared by Dr. Ruedy, was distributed to delegates at the conference.

than a guess. The correct result is obtained if the change in j during the rebound is taken into account. The formula for $p_1-p$ and $f_1-f$ then gives the following expression for $\ddot{y}$ at any time during the rebound.

$$\frac{\ddot{y}}{g} = a_1y^3+a_2y^2+a_3y+a_4$$

where the a's are constants depending on $p_1$, $j_1$, $p_o$, $j_o$, and E.

$$a_1 = -\frac{64}{3}\frac{E}{j_oa^4} = -\frac{64}{3a^4}\frac{E}{j_o}$$

$$a_2 = \frac{8E}{a^2}\frac{j_1}{j_op_1} = \frac{8}{a^2}\frac{E}{j_o}\frac{j_1}{p_1}$$

$$a_3 = -\frac{2}{3}\frac{Ej_1^2}{j_op_1^2} - \frac{8p_1}{a^2j_o} = -\frac{2}{3}\frac{E}{j_o}\frac{j_1^2}{p_1^2} - \frac{8}{j_o}\frac{p_1}{a^2}$$

$$a_4 = \frac{j_1}{j_o} - 1$$

an integration according to the formula

$$\int \ddot{y}\,dy = \int vdv = \frac{v^2}{2} - \frac{v_o^2}{2}$$

where v is the velocity, gives the equation

$$\frac{v^2}{2g} = \frac{a_1}{4}y^4 + \frac{a_2}{3}y^3 + \frac{a_3}{2}y^2 + a_4y + \frac{v_o^2}{2}$$

where v is the velocity of the midpoint of the span at the end of the rebound and $v_o$ the velocity at the beginning of the rebound. Both velocities are zero so that the rebound height $y_s$ is given by the cubic equation,

$$y_s^3 - 4f_1y_s^2 + \left(4f_1^2 + \frac{3}{4}\frac{p_1a^2}{E}\right)y_s - \frac{3}{16}a^4\frac{(j_1-j_o)}{E} = 0$$

(b) However, this derivation assumes that during the entire rebound the conductor retains sufficient tension to describe approximately a parabola. If, as is usual, the conductor is longer than the distance between towers, it may happen that at some stage the tension disappears and that the conductor moves freely upward until the remaining kinetic energy has been used up in work against gravity. For such an occurrence, the rebound height is the sum of the rebound height $\eta_e$ to the level at which the tension just disappears plus the rebound height $\eta_w$ in the unstretched state.

To calculate the first portion $\eta_e$, the method is the same as before, except that now in the formula for the weighed-down catenary p is zero at the end of the rebound whereas v in the expression for $v^2/2g$ differs from zero. The approximate equation for the catenary gives at $\eta_e$

$$\frac{j_e^2}{p_e^2} = \frac{j_1^2}{p_1^2} - \frac{24\, p_1}{a^2 E}$$

and, therefore,

$$\eta_e = f_1 - f_e = f_1 - \frac{a^2}{8}\sqrt{\frac{j_1^2}{p_1^2} - \frac{24 p_1}{a^2 E}} = f_1 - \sqrt{f_1^2 - \frac{3}{8}\frac{a^2}{E}\, p_1}$$

This expression is introduced into the equation for $\frac{v^2}{2g}$ and leads to

$$\frac{v_e^2}{2g} = - \eta_e + \frac{3}{4}\, \frac{p_1^2}{E j_o}$$

Here, $v_e$ is the velocity remaining at the centre of the span at the moment the tension vanishes. The corresponding kinetic energy

$$\frac{m v_e^2}{2} = mg\, \eta_w$$

is used up in the second stage of the rebound through the additional height $\eta_w$ so that

$$\frac{v_e^2}{2g} = \eta_w = -\eta_e + \frac{3}{4}\, \frac{p_1^2}{E j_o}$$

The total height of rebound is $\eta_w + \eta_e$ or

$$\eta_o = \frac{3}{4 j_o}\, \frac{p_1^2}{E}$$ regardless of the length of the span.

(c) There remains a third possibility that after having lost its tension, the conductor becomes stretched once more in its upward flight and vaulted upwards, the remaining energy serving not only to overcome gravity but also to store potential energy of tension in the conductor. The rebound then consists of the distance up to the height at which tension reappears and the remaining stretch along which the velocity is reduced to zero in the work performed against gravity and tension. The calculations show that the total rebound height is given by the cubic equation for $y_s$ as though the tension had never vanished.

This result leads to another problem, namely the question as to when the rebound height must be computed from the cubic equation, and then from the formula $\frac{3}{4}\frac{p_1^2}{j_o E}$. At the two limits, $y_e$, and $y_{Lo}$, that is, when the tension just vanishes at the end of the rebound (for $y_{eo}$) or just reappears again, (for $y_{Lo}$) both expressions must give the same result.

If the expression $y_{eo} = \frac{3}{4}\frac{p_1^2}{j_o E}$ is put equal to the expression $y_{eo} = f_1 - f$ for vanishing tension and speed, the rebound height can be eliminated and an equation for the limiting tension deduced. An equation of the sixth degree is obtained.

$$p_1^6 - \frac{4}{3} e p_1^3 - \left( \frac{e^2}{9 p_o^2} - \frac{8}{3} e p_o \right) p_1^2 + \frac{4}{9} e^2 = 0$$

where $e = a^2 E j_o^2$.

It has two changes in sign and, therefore, according to Descartes' rule, only two real roots; the larger one corresponds to the height $y_{Lo}$ at which the tension just reappears again and the smaller root to the height $y_{eo}$ at which the tension just vanishes at the end of the rebound. If the solutions of the equation are plotted in a diagram having the span length as horizontal axis and values of the tension $p_1$ as vertical axes, a curve is obtained enclosing all the tensions $p_1$ for which the rebound ends in the tensionless state at a given stringing tension $p_o$. With increasing stringing tension, this curve is shifted upward and to the right. If, for a given ice load and stringing tension, the calculation of the tension $p_1$ gives a value that lies to the left of the curve, and has a value smaller than the point at which the tangent to the curve is vertical, there is no rebound involving complete loss of tension, and the cubic equation must be used for computing the rebound height. If $p_1$ is represented by a point outside the region enclosed by the curve but lying higher than the point at which the tangent is vertical, rebound is associated with recovery in tension.

That is as far as Hunziker has treated the subject. Three tasks remained: (1) to work out simple methods of solving the equations (2) to compare the computed results with measurements, and (3) to study the oscillations following the rebound.

(1) By using $y = h/2f_1$, the cubic equation for the rebound height can be written as

$$y(1-y)^2 = \frac{12p_1^3}{a^2Ej_1^2}\left(1-\frac{j_o}{j_1} - y\right)$$

The product $y(1-y)^2$ can be plotted once for all on a convenient scale as a function of y. The right hand side of the equation is then represented by a straight line which intersects the y-axis at $1-\frac{j_o}{j_1}$ and which has the slope $\frac{-12p_1^3}{a^2Ej_1^2}$.

The intersection of this straight line with the curve representing the product $y(1-y)^2$ between $o < y < 1$ gives $y_s = y_s/2f_1$, as the solution of the cubic equation.

The equation for the curve surrounding the region for which the values mean rebound ending with complete loss of tension can be written as the product of two cubic equations each one of which can be solved separately.

(2) Experiments on actual spans were carried out by Perlick before a theory was available. Instead of subjecting the conductor to a uniformly distributed load, weights were suspended at separate points and no attempt was made to select the load in such a way that the tension would have been the same as if the load had been uniform. Accurate agreement between theory and experiment is, therefore, not to be expected. For an aluminum conductor, 240 ft. long, 3/8 in. in diameter, having a sag of 5 ft. when overloaded, and $1\frac{1}{2}$ ft. when free, the ratio $j_o/j_1$ is approximately 1/9.

| | |
|---|---|
| y (from cubic equation) | = 269 cm. |
| y (measured) | = 300 cm. |
| $y = 2(f_1-f_o)$ | = 220 cm. |
| $y = 2f_1(1-\frac{3}{2}\ \frac{j_o}{j_1})$ | = 258 cm. |

Other measurements give even closer agreement between the cubic equation and the measurements.

(3) When the constants $a_1$ to $a_4$ in the equation for $v^2/2g$ are calculated, it is found that the terms $a_1y^3 + a_2y^2$ are negligible for many spans and overloads so that the equation for the acceleration

reduces to $\frac{\ddot{y}}{g} \mp a_3 y + a_4$

The integration now leads to

$$y = \frac{a_4}{-a_3} (1 - \cos\sqrt{-a_3 g}\ t\ )$$

for the amplitude of the oscillations of the rebound and to

$$f = \frac{\sqrt{-a_3 g}}{2\pi}$$

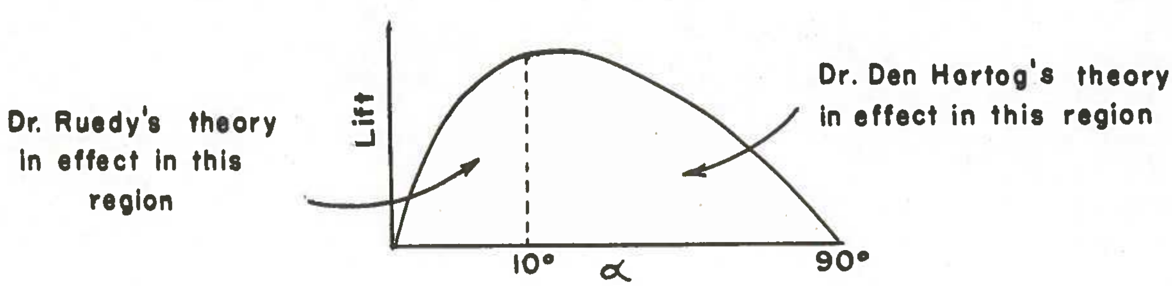
for the frequency of the oscillations. Calculations made by Mr. J.M. Kennedy indicate that for many spans the amplitudes and the frequency agree closely with those observed on galloping transmission lines. If measures are taken for the prevention of galloping, the service intertuptions caused by rebound also deserve attention.

Comments

(Note: Dr. Ruedy presented to the Conference a review of material covered in the above paper and the paper on page 12. The comments herewith refer to this review, as delivered.)

In discussing Dr. Ruedy's paper, Dr. Den Hartog said that he had tried Dr. Ruedy's experiment with the rubber band in both planes, and that when the bands were held in a vertical plane the motion of the conductor could be felt with the fingers, and this motion was of a considerably higher frequency than that obtained when bands were in a horizontal plane, due to the fact that the rubber is very much stiffer in the one plane than in the other.

He then illustrated, by means of the following lift-drag diagram, that Dr. Ruedy's explanation lay in the section typical of aerodynamic foils, whereas his own explanation lay at the other extreme of the vertical lift diagram. He agreed with Dr. Ruedy that for low values of $\alpha$ , galloping would have to be accompanied by coupled motion. Although he felt that there would be many more cases of galloping of the D-foil type then of Dr. Ruedy's flat section, he agreed that both cases demanded attention, and pointed out that the oscillation in both cases had to be proportional to the wind velocity.

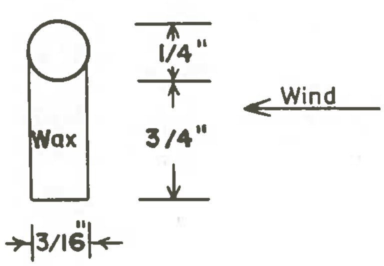


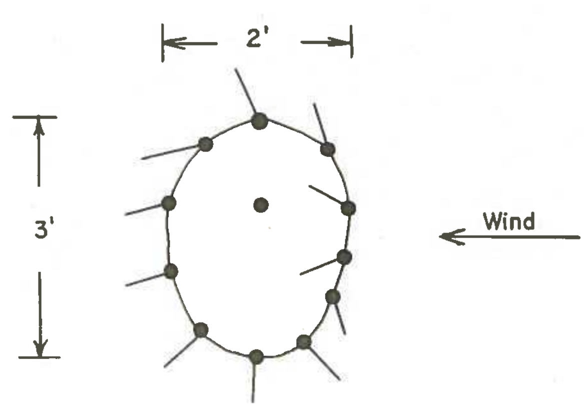
In commenting on Dr. Ruedy's paper, Mr. Becker stated that, while he was very much interested in the mechanism and theory of galloping, he felt that a full understanding of the theory might not necessarily be essential to a satisfactory solution of the galloping problem. However, knowledge of the theory or theories could be very important; for example: (a) If the presence of a torsional motion is largely necessary in the significant types of galloping, it may be possible to utilize this characteristic in damper design. (b) Special shapes or groupings of conductors may be of importance in reducing the galloping amplitude, depending upon the nature of the mechanism of galloping. (c) Knowledge of the mechanism would, through laboratory tests, permit determination of the maximum rate of energy input from the wind. This information would be of great value for damper design, and at present it certainly appears to be the most important piece of missing data in the galloping problem.

He mentioned that galloping can occur when the ice formation is smooth, without fins or appendages, and as thin as, say 1/8 inch. (According to Mr. Davison, as thin as 1/64 inch or less.) Indeed, there is growing evidence that it can occur on a round, or nearly round, conductor in the absence of ice. (For example, see AIEE Trans. Aug., 1942, p. 592.)

He mentioned that Mr. Stewart of the Buffalo-Niagara Power Co. wrote an article on a galloping conductor experiment in 1937. Mr. Stewart used a single 104 ft. span of 1/4" dia. ACSR with a waxen air-foil and a sag of 1.9 feet.

The conductor behaved somewhat like a skipping-rope, "rotating" as a single loop (fundamental) in an elliptical path, with a horizontal displacement of 2 feet and a vertical displacement of 3 feet. However, the minimum wind velocity which would put the conductor into motion was 25 mph at 90° to the span. The "rotation" rate was 107 rpm (or cpm). However, the natural frequency of this span was only about 44 cpm. This discrepancy in frequency does not, to his knowledge, appear to have been observed in natural galloping. He did not believe that the performance of Stewart's span was comparable to the bulk of the cases of galloping, although it likely did apply to some cases, particularly, some of those in which the glaze is decidedly elongated in the vertical direction. For such a glaze other mechanisms of galloping also are possible. With many ice coatings there would appear to be insufficient aerodynamic torque to produce the twisting that Stewart obtained.

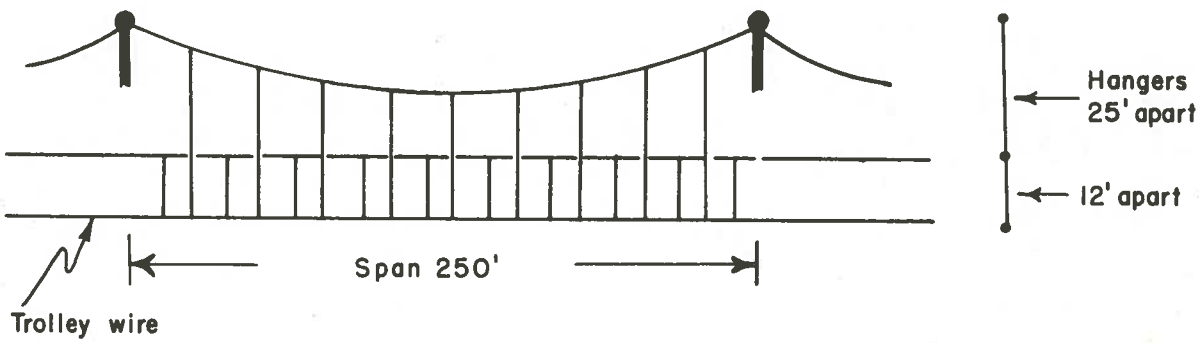



End View Showing
Successive Positions
Of Air Foil

Various Types of Galloping
(The Possibility of Torsional Oscillation)

Mr. Becker mentioned a type of galloping which occurs very frequently, namely, the galloping of aerial, lead-sheathed, telephone cables suspended by a steel carrier wire with approximately two-inch separation. These cables are up to 2.5 inches in diameter and may weigh up to 8 pounds per foot. These definitely are known also to gallop without ice (in the summer). The modes are one and two loops and the frequency follows the usual relationship with the sag. He felt that torsional oscillation was practically impossible in these cases, and also in a case involving trolley-wire suspensions of which movies were shown.

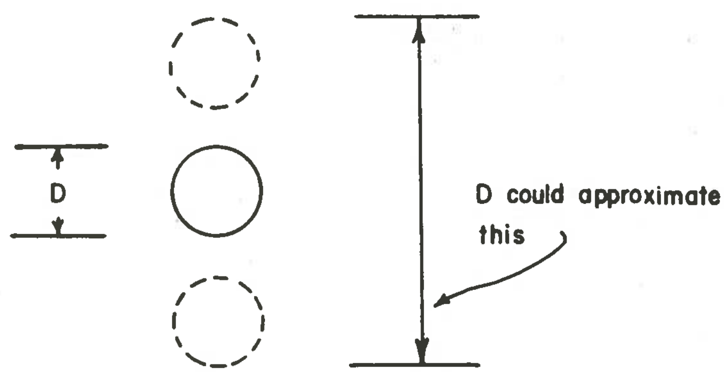



These assemblies moved as a whole, in one loop, and seemed to possess only the vertical or up-and-down motion. Because of friction it is difficult to see how any of the three cables could oscillate in torsion. (See also AIEE Trans. Aug., 1942, p.591, describing a catenary system, where the addition of extensive horizontal bracing with vertical stays failed to stop galloping. Chance of torsion here very remote.) A theory of galloping dependent upon torsion would hardly apply in these two oft-occurring types of galloping.

Mr. Dean asked Mr. Becker if he knew why the Tacoma Bridge possessed a torsional motion, since it was such a bulky structure. Mr. Becker pointed out that the oscillations of the Tacoma Bridge had always consisted of purely vertical waves until the last day. On that day the number of loops suddenly decreased to two, with a node at the center. Then a breakage occurred in one of the guys of the mid-span tie on one side of the bridge. It appears that the resulting unbalance threw one of the two vertically-oscillating main cables out of phase, causing a twisting in the roadway as one side went up while the other went down. This resulted in a purely torsional motion, in which one side of the bridge was 180° out of phase with the other. The wind was at an angle of 40° with the bridge, at 42 mph.

The laboratory investigations showed that the Tacoma Bridge oscillations should be either purely vertical or purely torsional. The cause of the oscillations of the Tacoma Bridge is now believed to be vortex discharge, the initial excitation being of a subharmonic nature. (See Proc. Am. Soc. Civil Eng., Sept.,1944, Discussions, page 1008. Also Civil Eng. Journal, July,1947, page 44).

In the Strouhal expression $f \propto \frac{V}{D}$, the usual constant of .18 to .22 (ft. and sec.) may give a theoretical frequency which differs widely from the resulting frequency of vibration for those cases where the amplitude of vibration is considerable. For such cases a better approximation may be had by considering D as the amplitude.




This effect, in conjunction with those of subharmonic resonance and wind obliquity, may possibly make feasible the production of galloping through vortex discharge, particularly in the case of large-diameter cables. Furthermore, these effects may augment any negative slope effects that might be present.

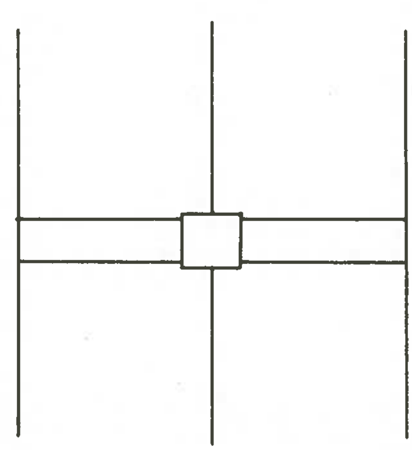
In discussing Dr. Ruedy's paper, he did not think that a small coating of ice could result in the necessary aerodynamic thrust or torque to cause torsional vibration, and he pointed out that a small coating of ice will not change the moment of inertia or stiffness sufficiently to bring the torsional frequency and the vertical frequency to approximately the same value, which Dr. Ruedy had stated was necessary for this type of motion. He illustrated the type of cross-section to which he was referring as shown below:

In the Maywood test line, the torsional frequency seemed to be of the order of ten times the vertical frequency. He then pointed out that in their test line using a stranded cable, the cable twists when manually moved up and down in the absence of wind, and he felt that this was a purely mechanical action due to the stranding of the conductor, although it might be caused by the presence of the D-section. The point in this is that a torsional motion might result from other than aerodynamic forces. In the case of a solid conductor, mechanically-induced torsion does not seem probable, unless mechanical effects of the ice can bring it about. Mechanically-induced torsion, as well as certain types of aerodynamically-induced torsion, may either help or hinder the galloping depending on the phase, etc. Therefore, caution is advised in interpreting the mere observance of a torsional motion in a galloping conductor. A transmission line conductor usually has low torsional rigidity and it should be occasion for surprise when it does not twist during galloping.

With a vertically oscillating conductor, it would seem that the glazed conductor cross section, which the relative wind "sees", may differ greatly in the up-stroke as compared with the down-stroke. Is it then correct to conclude that the aerodynamic torque may also vary considerably in the one stroke as compared with the other, and thereby bring about some torsional oscillation? In a similar manner, and depending upon the cross section "seen", it would appear that the drag may vary considerably in the up-stroke as compared with the down-stroke. If this is correct, it might help to explain the elliptical path often assumed by galloping conductors. The D-section usually gallops largely in a vertical plane and it tends to have a symmetrical cross section with respect to the relative wind.

Regarding Dr. Ruedy's statement that galloping did not occur in Europe, while this statement might hold for Continental Europe, there have been a number of cases in the British Isles. However, it was not considered to be a major problem there.

In discussing Dr. Ruedy's paper, Mr. Turner cited a case which had been brought to his attention of a barge, moored in a channel, and subjected to incoming and outgoing tides. The barge was moored as shown below and was anchored by means of two-inch-diameter cables, 100 feet



long. In this case, the flow of water caused a very high frequency vibration, having an amplitude of about three diameters, to take place in the cables and terrific heating of the cables occurred at the junction point of the boat and the cable. The heating was so intense that water poured on them boiled. He suggested that this might possibly bear some relation to the problem at hand. Mr. Becker felt that this cable vibration was the result of vortex discharge and that this could be compared to galloping in so far as his preceding remarks with reference to the Strouhal expression, etc., are applicable to galloping.

Dr. Ruedy, in commenting upon the discussion stimulated by his paper, pointed out that torsion was introduced because, in the theoretical analysis, the flat shape was assumed, and this shape was necessary for simplicity in calculation. So much work had been done on D sections already that it would have taken too long to wade through the literature on the subject before starting, and that in this case, he would be better advised to work on another simple section which could exist. He then pointed out that nobody has measured torsional motion in galloping to see if it does exist, and suggested that it would be very helpful if attempts were made to do so.

Regarding Dr. Den Hartog's comments on the use of the lift vs. drag curves, he stated that the distance to the crest of the curve was, in his experience, not 10° but 40°. He also pointed out that in the formula $L = CV^2a$, C is only constant for flat sections. Also, due to the difference in frequency, peaks occur in the amplitude of galloping. Another reason he gave for the use of a flat section is that in all the literature which he has perused, this type of conductor is referred to when galloping is mentioned. He did not maintain that rotation must accompany galloping in all cases; in other words, he did not think that galloping must be caused by a flat section, but that it may be the result of a flat section in some cases, and his analysis was to take care of these cases.

Regarding the Tacoma bridge, he said that the measures taken in creating the design for the new bridge showed that the engineers did not blame eddies for the disaster. Mr. Oldacre then pointed out that in the new bridge the ratio between the depth and the width was changed.

Mr. Becker then asked Dr. Ruedy if the torsional and vertical frequencies had to be of the same order. Dr. Ruedy agreed with this and said that the figures given by Mr. Becker did not agree with those which had been given to him by the Hydro. Mr. Becker said that he had made crude measurements in obtaining the figures and these had consisted of twisting the line at the center of the span and recording the frequency of oscillation. He also felt, from casual observations, that the ratios are of this order, i.e., ten times. Mr. Lawton said he believed that Mr. Becker's method would not give a true answer to the torsional frequency.

A Theory of Galloping Based on a Periodic Variation in Tension

Dr. Niven proposed a theory of galloping based on a periodic variation in tension, thus producing oscillation at the resonant frequency of the line. He pointed out that the facts requiring explanation are that galloping occurs on transmission lines in the absence of ice, and that any theory which is based on the assumption that ice must be present is fundamentally wrong. He went on to say that galloping can be created at any time, merely by varying the tension periodically, and he demonstrated this later in the day. This was done by means of a rope attached to a wire, pulled tightly and then gradually varied in tension, and galloping was obtained. To illustrate how this effect can be obtained from the wind forces, he pointed out that if the line is swaying in the wind, a pendulum motion from side to side will be obtained, and if this is of sufficient amplitude it may result in an up-and-down motion probably not in the same span, but possibly in one several spans away. When experiments were made to try out this idea with ice on the line, the ice tended to prevent the motion from occurring.

Periodic gusts could not cause galloping, primarily because these would have to occur at the frequency at which the line was in resonance, and this would be too great a coincidence to expect. However, a gust travelling along a wire would be one possibility, causing a travelling tension which would make the line gallop.

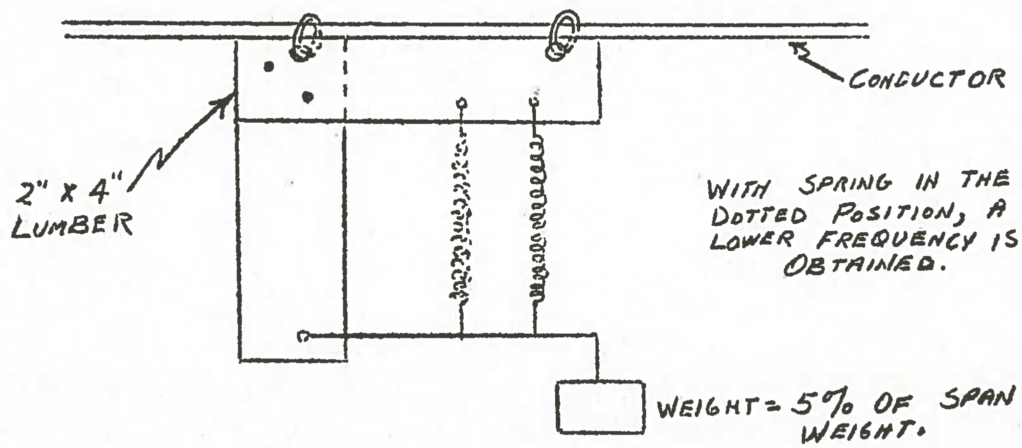
Discussion: Mr. Henry remarked that they had tried artificial impulses on lines similar to Dr. Niven's method, and that they had been able to get practically any form of galloping by a variation of the tension and the frequency. On this line, they had used snubber buffers, and had found that the snubbers worked if adjusted properly on a single span, but they were ineffective on a three-span line. He wondered if the travelling wave effect was being investigated sufficiently and he felt that all of the movies had shown that there were a large number of travelling waves involved.

Commenting on Mr. Henry's statement, Mr. Oldacre said that calculations showed that there would be no movement of insulators ten spans away from a break in the conductor. This applied to a 220-kv line.

Mr. Becker was of the opinion that galloping could not be eliminated by any practical variation in the tension of the conductor while in service. The clearance and strength tolerances of many transmission lines do not permit of more than minor changes in sag or tension. However, in this regard he has, it appears, experienced a very pronounced difference in galloping activity and amplitude between a sag of 6.5 feet and 3.9 feet on the 250-foot span test line. Under certain conditions, at least, the 6.5 ft. sag resulted in amplitudes greater than the sag ratios would indicate. The matter is still under study.

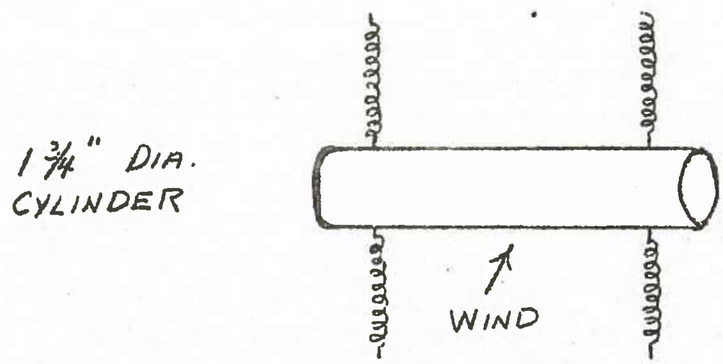
Commenting on travelling wave effects, Mr. Runciman suggested using a pendulum mounted on the line near the insulator. This pendulum would have to be attached in such a manner that it would be out of phase with a wave coming back along the wire and thus damp out the wave motion.

Mr. Becker said he believed that a regular pendulum would be too cumbersome for oscillations of the order of 20 cpm. The following type of compact suspension can be made to give oscillations of this order.




This principle (dynamic vibration absorber) seemed to prove rather effective on small oscillating airfoils. Theoretically, this device does not absorb energy, but merely causes a transfer to itself of the motion of the parent body. However, in practice the device apparently can be designed so that it absorbs energy. They tried a weight suspended as a pendulum from the test line conductor clamp, both free to swing and rigid with the clamp. Thus far, neither suspension produced any great effect unless used in conjunction with damping or interference devices. Greatly increasing the moment of inertia of the suspended weight appears to have interesting possibilities.

He then mentioned some wind tunnel tests wherein a cylinder, which was stable in 90° winds of 15 to 28 mph, oscillated violently when the wind became oblique. He felt that this behaviour should be investigated.




Mr. Becker then mentioned using a device very similar to the arm and weight suggested by Mr. Runciman. It was located approximately 50 feet from the tower on a 250 foot span. The weight, about 6 pounds, was mounted at the end of a 14-inch arm. The span of bare conductor was caused to oscillate by hand at 24 inches amplitude in 2 loops, the weight being moved up and down with the wire. When the weight was released the oscillation was largely stopped in 4 or 5 cycles.

<u>Aerodynamic Analogies</u>

Mr. Uffen said that a sound understanding of the fundamentals involved was a prerequisite to the solution of the problem. If galloping is analogous to stall flutter, which is in the realm covered by Dr. Den Hartog's theory, restraint will not stop it. If it is analogous to classical flutter, as indicated in Dr. Ruedy's paper, restraint might help. He pointed out that stall flutter is characterized by a single degree of freedom, and the frequency is dependent upon the natural stiffness, and the amplitude dependent upon damping. If stall flutter is the case, varying the restraint will not stop the galloping, but only alter the frequency and slightly alter the amplitude. Classical flutter, however, is characterized by the rotation mentioned by Dr. Ruedy, and also by the fact that it has a series of critical speeds, and this agrees with some of the observations made. Therefore, galloping is made up of more than one form. The twist in the conductor could be satisfactorily reported with a torsional vibrometer. This could be cheaply done over the whole line, putting vibrometers on every third or fifth span and in this way a statistical average could be obtained, and from an analysis of these results it would be possible to ascertain the type of galloping which was most predominant. In this method of recording, the recorded amplitude would be greatly increased if the galloping were of the classical type. Once it has been decided which form of galloping is most prevalent, then we might possibly limit our thinking to concentrate on the elimination of this particular form, and in this way, possibly eliminate the majority of the cases of galloping.

Mr. Becker said that the vibratory coupled motion, or classical flutter of aeroplane wings, appears to occur only within a narrow range of "reduced frequencies"

$$\frac{\pi \times \text{Freq.} \times \text{Chord}}{\text{VEL.}}$$

say, perhaps 0.3 to 1.8. However, with a typical case of galloping, the reduced frequency may be of the order of only .006. Therefore, the phase difference between the lift and the angle of attack (non-uniform motion) must be very small. Possibly this indicates that classical flutter could hardly be expected to occur with such a typically glazed conductor? For the production of torsion there would remain such possibilities as mechanically-induced torsion, aerodynamically-induced torsion similar to that experienced in Stewart's experiment, etc.

## V

## PROPOSALS FOR FURTHER RESEARCH

### General

Mr. Dean said that it would be necessary to install a great deal of equipment, and to wait a long time before useful data could be obtained. The solution, he thought, would have to be very broad. He said that this problem is very similar in this respect to that which they ran into in the case of lightning. In this case, many years were involved in the solution of the problem, and he believed that the same would be true now; in the meantime, it will be necessary to go ahead without all of the desired information. The information which he feels should be obtained as soon as possible is how much twisting occurs in the conductor when galloping naturally. Money will have to be poured into this work, and it may take ten or more years to get the necessary results, but they will be obtained in the long run.

Dr. Ruedy maintained that too much equipment should not be laid out for the investigation of conductor rotation, but he would like people in the field to continue to make observations to determine whether or not this does take place. He pointed out that for flat conductors the angle of rotation is limited to less than 40°, and in this case it means that the rotation per foot is of the order of 1°; thus, the recorders would have to be placed near the middle of the span. He would appreciate getting information on the rotational frequency of conductors in the field.

In addition to rotation, he would like to know of cases of vertical galloping in which the downward galloping exceeds the upward galloping. In the literature which he has reviewed, most of the cases mentioned were of upward galloping, and he only ran across one case of downward galloping, i.e; the case where the downward motion exceeds the upward motion. He felt that information on this would add to our knowledge of the subject.

He then mentioned that the two cases covered by his and Dr. Den Hartog's theory were at the two extremes, and that there are many shapes in between, and also many other factors which modify the results, such as the eddies which cause aeolian vibration and are still present, even though the vibration itself has been damped out.

Mr. Henry made the following suggestions, which he felt might possibly aid in the suppression of galloping:

(a) Since galloping involves the mechanical resonant frequency of the line, it might be possible to vary the natural periods by means of unequal spacings, and thus to prevent galloping, or at least to limit it. This could easily be accomplished in the case of new lines, but would be difficult on existing structures.

(b) By stringing the line to different sags in the same span, by decreasing tension in the bottom and middle conductors, since tension could not conveniently be increased, it might at least be possible to minimize galloping.

Recording of Data

Dr. Hogg believed that, in future, attempts should be made to record the torsional movement of the conductors and also the losses in torsion and bending. He would also like to see recorded the tension in the conductors, and the suspension point movement. He suggested that in all cases of natural galloping, records should be made in writing, complete with diagrams, and these should be circulated. He would like to see in these records data on the wind direction and velocity, and the translational and torsional amplitudes at as many points on the line as possible. He felt that this would give some indication as to the causes of galloping. He stated that during the conference he had been struck by the fact that many things had been tried, but that there were no records, and he would like to see these attempts down in writing so that duplication might be avoided.

Regarding the use of test lines, Mr. Uffen said that he would like to see those equipped with such instruments do as much recording as possible, especially paying attention to the end motion of the wire, the end motion of the tower, and the mode of displacement of the wire. In his opinion, it would be much better if this were done on photographic film. In this way, it would be possible to get simultaneous records of the amplitudes and phases, and he believed that this was very important. All of these measurements could be fairly easily accomplished. He felt that twisting due to the aerodynamic forces, and that due to the lay of the line, should be recorded along with all weather data. In his opinion, records should not consist of jotted down observations, but should be a continuous record, especially in the case of the weather data and the wind directions and velocities.

Initiation of Galloping

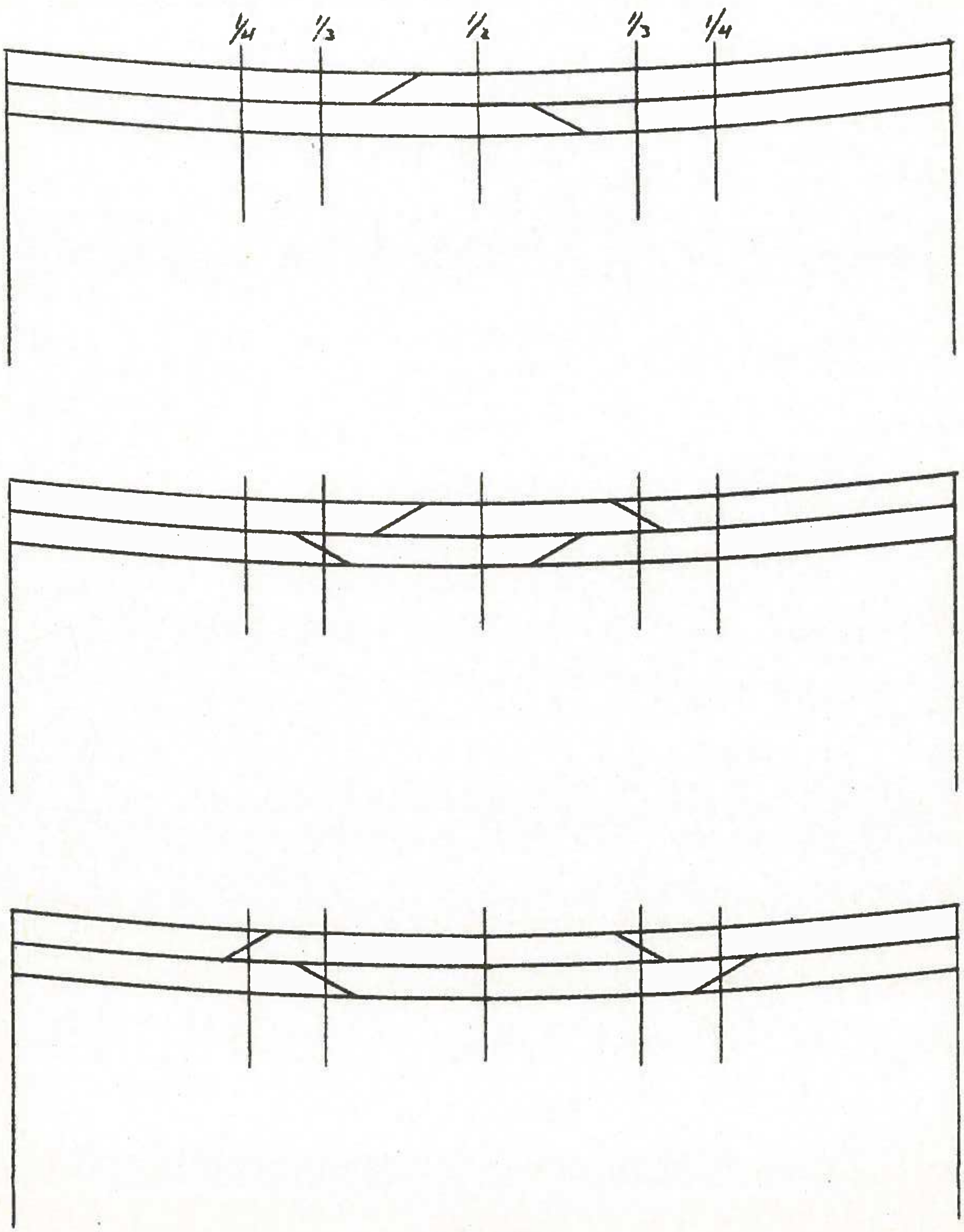
From his own observations on galloping, Mr. Davidson said he was convinced that the forces involved are very small, and take a long time to cause galloping to begin; a study of initiation might give some information on how galloping can be damped, and thus prevented, instead of waiting for the line to get into the galloping stage. The type of motion in the initial stages might require quite different damping from that in the final.

Mr. Runciman suggested using a motor and gear train and attaching this, through a spring, to a line connected to the conductor, as a means of starting galloping. This spring would have to be calibrated for tension of the order of one ounce, and by using a fixed input, the line could be made to start galloping, and a determination of the time required to build up to any given amplitude could be recorded. Thus, a plot of time vs amplitude would be obtained for galloping for any given input force. He believed that only very small forces are involved in this phenomenon. The revolutions would have to be of a low value, and, in this way, the input force to the line could be measured each time.

Regarding test lines, Mr. Becker pointed out that the main difficulty is that we do not have any conception of the energizing effects present, as compared with those present in the cases of natural galloping, and he felt that this correlation is very important. Possibly devices tried unsuccessfully on test lines might be quite effective in the cases of natural galloping, and, consequently, he would like to see an attempt made to determine the rate of build-up in natural galloping. It might be possible to do this by stopping the galloping on a de-energized line, and then releasing the line and timing the build-up, although he did not feel that it would be easy to get all of the conditions right at a suitable time. If this were also done on test lines, the relationship between the two could then be obtained.

Dampers

Interphase Ties: Mr. Henry suggested that a mechanical cross-tie, which would have to be insulated for the full voltage, could be fastened between the conductors and this might possibly effect the necessary damping. In this connection, it might be possible to use some of the new synthetics, but only if the crossties were tension members. The following sketches show how these would be inserted:



Note that attachments are not made to any conductor at the mid-point, or the one-third points, or the one-fourth points in the span. It would seem that such ties would be most likely to be effective if they were installed at an angle of 30°, or less, to the horizontal conductor. In this way, the point of attachment of any given tie to one conductor would be different from the point of attachment to the adjacent conductor by a distance at least equal to twice the spacing between the two conductors. It would seem that some such arrangement of inter-phase ties might result in a combination which would have no natural period of vibration and would not respond to the galloping phenomenon.

Movies taken at Chicago showed the three conductors galloping in synchronism when they were tied together with vertical ties of ordinary string, indicating that a very small force will cause galloping in a conductor at a frequency which may be a little different than the natural frequency of the conductor. However, if these ties are placed at irregular intervals and at a considerable slope, this tendency may be broken up.

Dr. Niven said that Mr. Henry's proposal would not be practical, since the insulated rod would have to be in position all of the time and it would be impossible to get an insulator in rod form which could be relied upon as an insulator all of the time.

With regard to Mr. Henry's mention of interconnecting vertically-separated phases with an insulating tie, Mr. Becker said that they had tried this and the results would be shown in one of the movies. Apparently, a single tie is ample to direct and maintain the conductors in oscillations of the same phase and at identical frequencies, thereby preventing contact.

Mr. Becker stated that they had tried ties between horizontally displaced oscillating models in the laboratory and were able to obtain a considerable suppression of amplitude when weights were used in conjunction with the ties.

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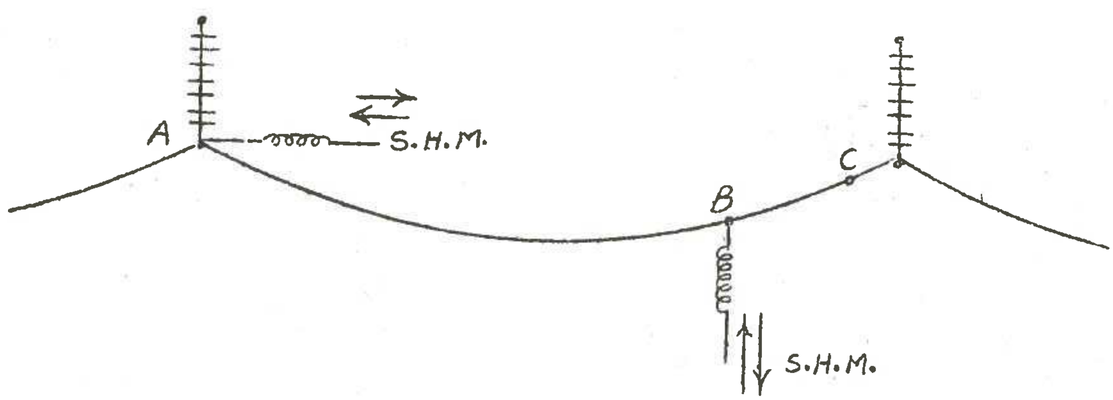
Mr. Oldacre reported that conferences were held by members of the Chicago group with several engineers who have studied this problem from a theoretical point of view. There was quite general agreement that any damping device would have to be of the energy absorbing type. It was also believed that a full and correct understanding of the theory of galloping was not essential for the design of satisfactory damping devices. It was believed that damping devices could be designed if the amount of energy involved in galloping was determined.

Regarding tests on mitigating devices, Mr. Becker believed it might be possible to give them a preliminary evaluation by forcing the line into an oscillation by mechanical means and then measuring the decrement with a damper in place. If reliable, this might provide a rapid check for variations of the same damper and for the many gadgets which have been suggested. He believed there might be some possibility also in testing dampers on a line which is oscillated by mechanical means through a spring, in such a manner that the power input could be controlled and measured. This might be possible by delivering the power to the line through a coil spring actuated by a reciprocating simple harmonic motion at the frequency of the desired galloping mode. Neither method is free of limitations and drawbacks.




With a given power input the resulting equilibrium amplitude would be measured both with, and without, the damper in place. Application of the spring force at A gives the one-loop gallop. Application at the quarter point B gives the two-loop mode. Application at C (say 10 or 20 ft. from support) may also give a satisfactory two-loop gallop. With certain types of dampers the only dependable test would be on a wind-actuated line.

Mr. Runciman said that in his opinion it would be advisable to use the Tebo type of damper at the 35-foot point to see how they would act under normal ice conditions, since Mr. Becker had indicated the diffictuly in trying them on test lines due to the rotation of airfoil by the dampers. He pointed out that the Stockbridge type has a different kind of motion.

(Note - At the "Informal Discussion of Galloping Conductors" held in New York, January 31st, 1949, there was some discussion as to whether either Stockbridge or T and B dampers might reduce galloping. General opinion was that these would be inadequate, although it was recalled that one or two lines that had been equipped with dampers had no further galloping. It is not known, however, that galloping conditions had occurred since the dampers were installed.)

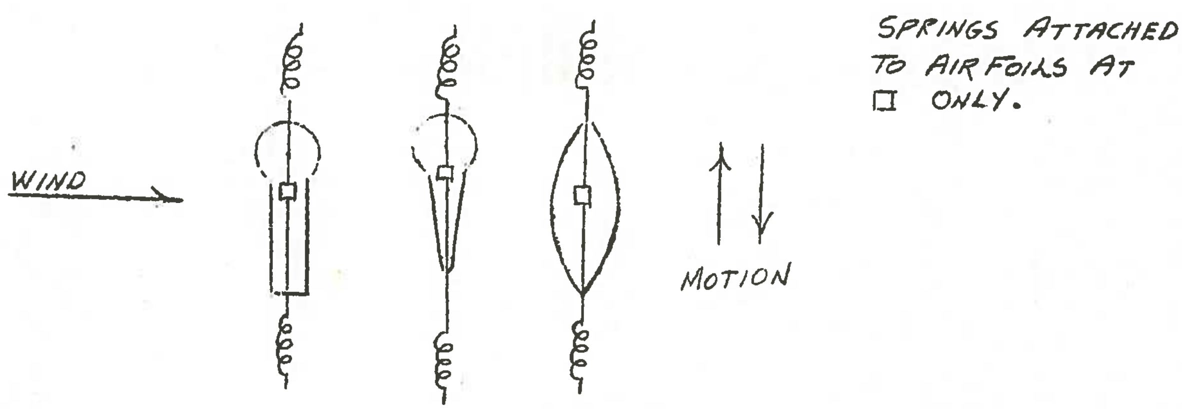
Mr. Henry pointed out that Mr. Runciman is interested in seeing what happens when a longer arm and a heavier weight are used than is customary in the Tebo dampers. Existing equipment did not have a long enough arm or a heavy enough weight for this purpose. It was suggested at this point that some of the old dampers which the Hydro had on hand might be satisfactory.

Test Sections

Regarding the energizing effects, Mr. Becker believed that lift and drag data should be obtained for typical glaze sections. These are available for Stewart's airfoil, and he believes the data for the D section will soon be available at Notre Dame. Similar data for thinly glazed conductors may be of use in determining whether the galloping which they exhibit in the field is associated with the negative slope of the lift curve. In this connection it may be necessary to investigate the dynamic lift as well as the static lift.

Most laboratory work on galloping conductors has been at high frequencies, with inadequate provision for torsional motion, and only with 90° winds. Some of the aerodynamic reactions at the low frequencies associated with most galloping may differ considerably, or be absent, at high frequencies, and vice versa.

Sections such as those in the figure below were stable in 90° winds at velocities above 5 to 7 mph. (The spring suspension used was comparatively stiff in torsion). However, when the wind became oblique, they were quite unstable and oscillated without any torsional motion. The D section in these wind tunnel tests was stable at 90° above approximately 12 mph, but a decrease in wind angle to 70°, or beyond, resulted in violent instability with no torsional motion. The experimental line, particularly the single-span line, appears to exhibit a similar behaviour. A possible explanation for this is given in the recent AIEE paper on galloping.

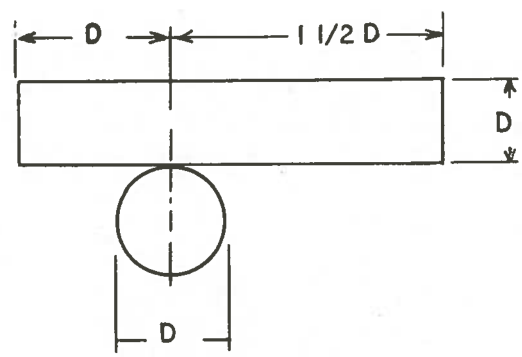


Mr. Speight desired to know whether anybody at the Conference knew of any obvious disadvantages to the use of test lines, wherein the results obtained do not agree with those obtained in natural galloping.

Mr. Oldacre said that test lines to date have caused difficulty mainly in keeping the D sections in order, and he suggested that if a better method could be found for making these sections than is used at present, it would be very acceptable. Regarding the use of D sections, he said that it is now generally accepted that if galloping can be stopped on a line equipped with D sections, it would be easy to stop it on a natural line.

Dr. Den Hartog added that, at present, as far as he knows, the D section is the most useful for simulating galloping, but he pointed out that some other section might be devised which would prove to be superior.

Mr. Davison suggested that some investigation should be made with the following section:

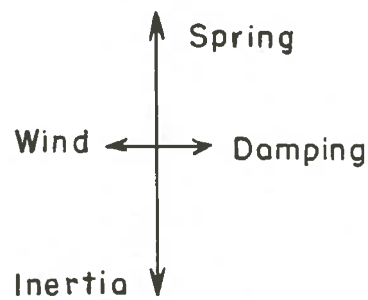



This section is the one suggested by Mr. Riddell, and it would be a very good section to investigate.

Water Tunnel

Mr. Campbell suggested that possibly the use of a water tunnel, rather than a wind tunnel, would enable the compilation of more complete data on the mechanism of galloping conductors, since the vibration would be slower and the forces larger. He suggested taking a small length of any section, such as the D section, and imposing forces on it to make it oscillate, and then measuring the energy fed in causing this section to gallop. This would give some idea of the order of magnitude of the energy which would have to be damped. He pointed out that these forces would be very small. Mr. Campbell stated that, in his opinion, field observations will supply the data much faster than any other method.

Regarding Mr. Campbell's suggestion, Dr. Den Hartog pointed out that it would be very difficult to measure all the forces involved. These forces are four in number, and are those attributable to (1) spring input, (2) wind, (3) damping, (4) inertia - and he showed, with the accompanying diagram, the phase relationships in which these forces act, and pointed out that the wind forces are very much smaller than the spring forces.




He felt that this information would be very useful if it could be obtained, and that it might possibly be obtained by making the whole apparatus very light and using very light springs, being careful to keep the hysteresis loss as low as possible, and by using a large area, keeping the natural damping as small as possible. In addition, he felt that by measuring the growth curves with wind and the decay curves without wind, the information could be obtained from their differences. Mr. Campbell then pointed out that his suggestion had involved a forced oscillation requiring no springs, and that a large section would have the wrong Reynold's number, if this was important, but Dr. Den Hartog felt that this was not important. It was then suggested that, by using two models at once, one in the wind and one not in the wind, and using a Wheatstone bridge arrangement to measure the difference between the forces on the two models, it might be possible to get these forces directly. Dr. Den Hartog felt that this would introduce so many errors that the results would be lost.

## Research Programs

### Proposed Tests at Carnegie-Illinois Steel Corporation Plant, Gary, Indiana*

The Gary Works of the Carnegie-Illinois Steel Corporation have some 22-kv lines on the steel towers within the plant and close to the shore of Lake Michigan, that are subject to galloping several times each winter. The trouble is becoming more serious, due to a change in power supply arrangements within the plant, and it becomes more important to avoid service interruption due to this cause. The Utilities Research group met with the Gary Works engineers several times to discuss the problem, and to work out a method of co-operative observation which might give some of the definite data that has been sought so many times on lines at other locations.

Most of the lines in difficulty have conductors of 636,000 ACSR on towers designed for 4/0 copper. The conductor spacing on part of these towers is designed for 66-kv service, while the others are designed for 22-kv service. All lines operate at 22-kv. The spans are 500 to 600 feet long. A part of the lines are within several hundred feet of the shore of Lake Michigan and parallel to the shore. There is an embankment along the shore at this place ranging from 15 to 30 feet above the water level. When the winds are from the northerly directions, a considerable amount of spray is blown over the adjacent shore area apparently onto the conductors, which lie in a generally east and west direction. Some other lines are in an approximate north and south direction, and they are also affected during some of the storms.

The plans contemplate setting up observation posts near several of the lines so that measurement of galloping can be made on both vertical and horizontal planes and recorded photographically. Small buildings are available for installation of test equipment so that the weather will not be too much of a handicap. These buildings will be arranged so that they can be moved to the most suitable locations. It has been stated that a large portion of the galloping occurs at night, and arrangements are being made for night-time illumination of the conductors. As an aid in making night-time photographs, small targets of Scotch-lite tape will be tried. Targets are also to be installed so that rotation of the conductor can be measured. It is planned to make tests within the next few weeks to see if these methods will be suitable under actual galloping conditions. To supplement the photograph records, some military gun sights have been obtained. These have a reticle installed in them, and they will be calibrated for measuring conductor movement.

Complete weather observations are to be made with suitable instruments.

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* An extract from the review prepared by Mr. Oldacre and distributed to delegates at the conference.

It is planned to install two test conductors on the steel towers at a safe distance below the line conductors, but at a minimum of 25 feet above the ground, for more detailed observation of the ice formation as to shape, kind, etc., and also to study galloping that might occur on such test conductors. Possibly five spans will be installed, dead-ended at each end and with suspension insulators at intermediate points. One conductor will be 636,000 ACSR duplicate of the tower, and the other will be 300,000 circular mil copper, the size frequently used in this area on other lines. If observation warrants, air foils can be installed on these test-line conductors next spring for further test purposes.

Due to some previous observations made by the Gary engineers, they are planning to move the Stockbridge dampers, now 9 feet from the tower, to a point about 35 feet from the tower, to see whether this will be effective in minimizing galloping.

### Additional Work Contemplated on the Public Service Company of Northern Illinois System*

It is possible that several spans of conductor will be installed on one of the 132-kv tower lines and equipped with the cross-ties mentioned earlier. This conductor will not be energized, but will be used solely for test observations. It is planned to have this installed before the sleet period occurs. It is also contemplated that a new test line, similar to that at Maywood, will be erected at a location where the wind conditions will be more favourable than at Maywood. This line will be equipped with an air foil and will be available for studies of various means of damping.

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Mr. Oldacre was of the opinion that observations should be made with a view to aiding the formation of a theory of galloping and calculation of the path of motion of the galloping conductors. His company is interested in, first, what can be done to existing lines to minimize galloping; this includes the design of dampers or other devices; second, what should be the design basis for lines to minimize the trouble.

He stated that, during the coming winter, they hoped to be able to measure the following four factors in galloping: (1) horizontal motion, (2) vertical motion, (3) movement of the insulators, (4) weather data. He suggested that they might string two more conductors 25 feet from the ground on one of their existing lines, using copper for one and ACSR for the other. They are also going to try to measure the torsional movement, and, by means of Scotch-lite tape fastened to the conductors, they are going to attempt night-time photography of the phenomena, as opinion seems to indicate that most of the cases of galloping occur at night.

* An extract from the review prepared by Mr. Oldacre and distributed to delegates at the conference.

Proposed Test Line of Hydro-Electric Power Commission of Ontario - Damping Device

Dr. Hogg reported on the test line which the Hydro-Electric Power Commission of Ontario is now building, the completion of which has been delayed by difficulty in getting the necessary labor. By making use of new and existing structures, a line will be obtained consisting of a 575-foot span, three 550-foot spans, and one 225-foot span. Conductors can also be erected on these structures to give a line having the 575-foot span, two 825-foot spans, and the 225-foot span. The conductors will go to ground anchors at each end of the line. The 225-foot span is incidental and is not to be used in the test work. The suspension points on this line will be about 45 feet from the ground The line will run 20° off the north-and-south line, in a northeasterly-southwesterly direction, in reasonably unobstructed country. The first conductor to be erected will be a 336,400 ACSR (30 aluminum, 7 steel), which will be equipped with D-shaped wood sections made of one-inch quarter round.

In planning the operation of this line, the Commission is interested in obtaining the opinions of others as to what tests should be conducted. If those engaged in theoretical work on the problem will indicate what experimental data they require, an effort will be made to obtain them.

One device to be tested as a damper has been suggested by Mr. Tebo. This consists of a split pulley-shaped piece which clamps on the line, and carries a weight suspended at the end of a rope or chain, the rope being wrapped once or twice around the pulley. This makes use of the conductor as a torsional spring to produce a low-frequency system, which may give an effective amount of damping. It is thought that this device may need to be installed at a considerable distance (say, one-quarter of the span) from the suspension point of the conductor.

Program Proposed by Dr. Den Hartog

Dr. Den Hartog had three suggestions for the lines which research should take:

(1) Run lift and drag tests in the wind tunnel at various angles of incidence (0° to 360°) for D and other sections such as are likely to occur in a sleet storm. Choose not more than four different sections: D, round with a small ice deposit on one side, medium deposit, a typical large deposit. Do these experiments at full scale, with actual wind velocities from 10 to 50 mph. These tests are duplicates of what is now done at Notre-Dame by Harris.

(2) Simultaneously with (1), and on the same sections, find by experiment the dynamic forces at motions $\theta = \theta_{max} \sin \omega t$, for actually-occurring values of $\theta_{max}$ and $\omega$. This is to be done by the test methods that the aircraft flutter experts have devised for measuring the air forces on a fluttering wing.

(3) For, say, six different sizes of widely used transmission line, run tests determining:

(a) the torsional stiffness, i.e. angle twist vs moment

(b) the hysteresis loss in torsion for various moments

(c) the hysteresis loss in bending

All of these should be found as a function of the tension.

Possibly this information is already available to the Power Companies or in the literature; if so, a comprehensive report of existing test results is satisfactory.

Objective

When the above information is available, an analysis can be made of the whole line with the object of finding the specifications for a suitable damper. Dampers designed on the basis of this analysis should then be installed on experimental lines.

This program does not pursue Dr. Ruedy's ideas, which are very fruitful, and a similar program for the same four cross-sections applying Dr. Ruedy's idea and suggested by Dr. Ruedy, should be given high priority. Regarding the program of observation at Gary, the program outline by Mr. Oldacre is quite complete, and should give very valuable information. Dr. Den Hartog, in discussing torsional-type dampers whereby the torsional hysteresis of the line itself would be employed, said that he had made a few rough calculations and it seemed to him that this type of damping would involve a damper of excessively large dimension.

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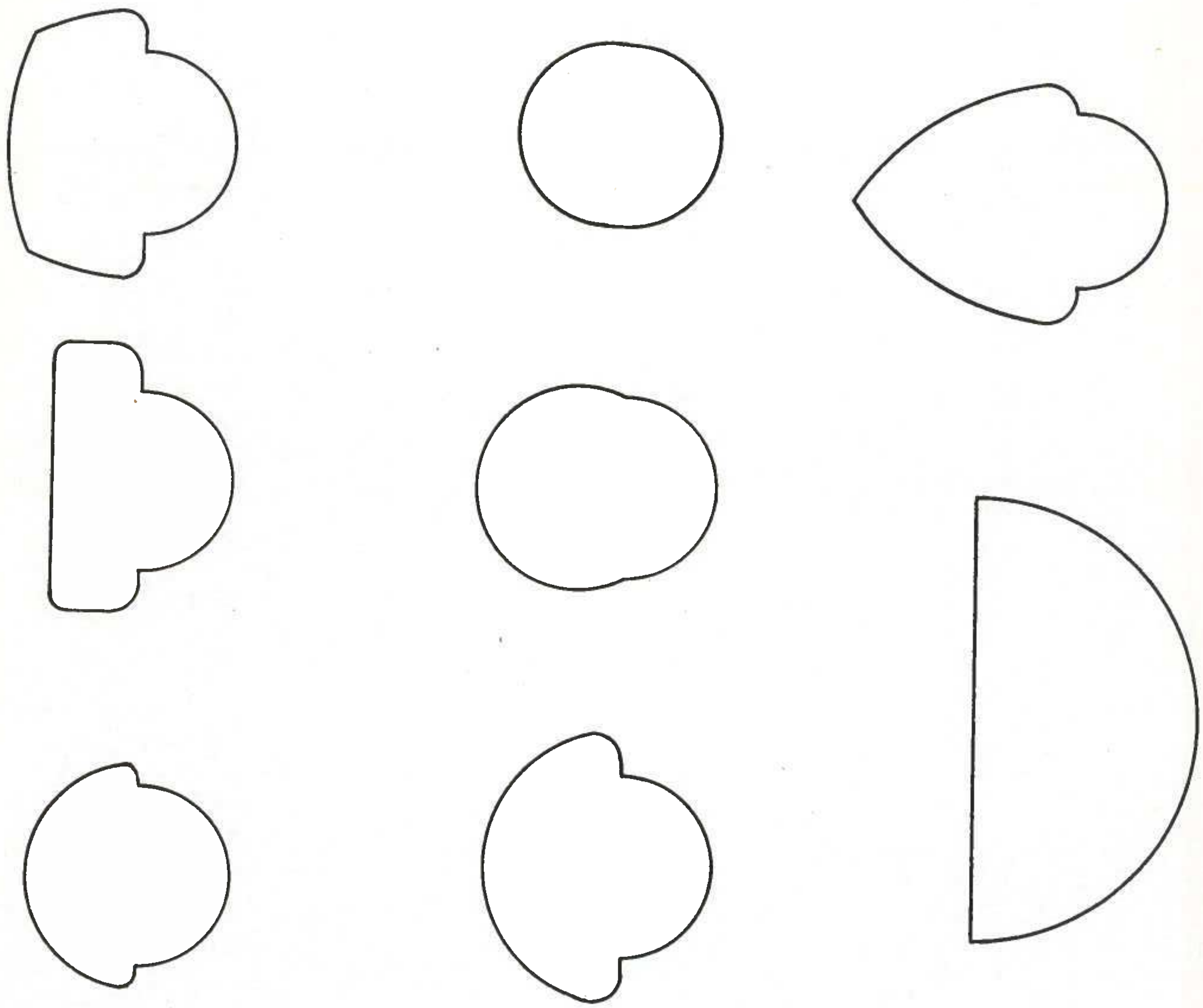
In accordance with these proposals, the Division of Mechanical Engineering of the National Research Council of Canada has commenced tests on a number of sections representing conductors with coatings of ice, as shown on the following page. The models will span a wind tunnel two feet in width, where they can be rotated 360°, yawed up to 45° and can be tested at steady speeds up to 90 feet per second. The lift, drag and pitching moment will be measured in each case and some investigation of the stability will be made.



Sections Undergoing Tests

at the National Research Council of Canada

(full size)

Technical Correlation

Mr. Dobson said that duplication would be desirable, since this would allow the elimination of some of the errors which creep in in this type of work. He suggested that it might be feasible at this time to revise their initial program which involved each group proceeding independently and correlating the results.

Mr. Oldacre felt that they should continue as they have done up to the present, and agreed that duplication would be good. He said that since the utility groups are on opposite sides of the border, it would be difficult to arrange for joint financing of a program. However, the work being done by the various groups should be closely co-ordinated from a technical viewpoint.

Mr. Davison suggested that the information gathered should all be sent to some central authority, such as Mr. Oldacre.

Mr. Henry stated that the transmission and distribution committee of the Edison Electric Institute has undertaken to collect the information derived from tests and forward it to Mr. Oldacre. This organization is a continuing headquarters staff, and their address in New York can be given to the various utilities, this address being a permanent one. He feels that this would bring in much more information in the future than they had received up to the present.