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Papers presented at
The IEEE Power Engineering Society
1979 Summer Meeting,
July 15, 1979.

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THE INFLUENCE OF SPACER DYNAMIC PROPERTIES IN THE CONTROL OF BUNDLE CONDUCTOR MOTION.

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ABSTRACT: This paper presents the results of a field investigation on systems of either damping or non-damping articulated spacers with regards to aeolian vibrations, wake-induced oscillations and rain vibrations. Each test out of a program of five was systematically carried out on a comparative basis at the Magdalen Islands test line. It is shown that a low stiffness is desirable in spacer-dampers but that damping capacity is not a must for the attenuation of subspan oscillation.

INTRODUCTION

Bundled conductors for the transmission of electrical energy at EHV level have now been in use for many years. Although, in general, bundled lines are less prone to aeolian vibrations which were known to exist on single lines, it was soon recognized that, in difficult environnements, they nevertheless require protective devices such as line dampers, in addition to spacers which are needed to preserve the geometry. The spacer-damper concept came up as it was proposed to use solely spacers to provide the required protection. Spacer-dampers were then also assigned the further task of controlling subspan oscillations as these became identified to be potentially dangerous. Today, many types of spacers either damping or non-damping are commercially available.

During recent years, many authors[1-14] have reported theoretical or experimental work on related topics such as the mechanism and the features of the various wind-induced phenomena encountered, the prediction of bundled conductor response to wind excitation, spacer design and placement, etc ..

However, many questions in connection with spacer performance are still debated. In particular, there is no general agreement upon the necessity of incorporating damping in flexible spacers in order to properly control subspan oscillations[15]. Also, more work is needed to achieve, for any given application, the optimisation of spacer-damper dynamic characteristics, such as inertia, stiffness and damping.

This report presents the results of a test line investigation which, it is hoped, will contribute to enlighten some of the questions raised in the paragraph above.

TESTING FACILITIES

All tests were carried out at the Magdalen Islands test line which has been fully described in reference 3. Briefly however, its main features are four portal type towers 100 ft. high x 50 ft. wide and two ground level anchoring bases making up three suspension spans of 900 ft., 1200 ft. and 1500 ft. respectively and two dead-end spans of 800 ft. (Fig. 1). The test line is erected over a sand dune close to the sea thus being exposed to very low turbulence winds of various intensities depending upon seasons.

For these tests, two bundles of four Carillon conductors at 18 in. spacing in square configuration were strung. Characteristics of the Carillon conductor are: stranding, 7 strands of 0.0870" diameter

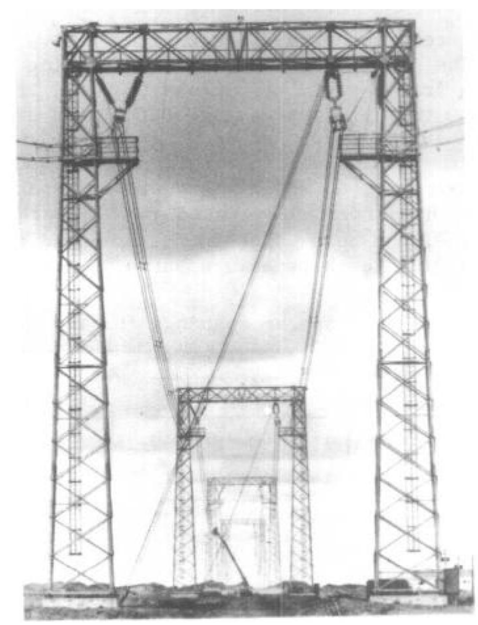

FIG. 1 The Magdalen Islands test line.

steel and 42 stands of 0.1565" diameter aliminium; overall diameter, 1.200"; weight, 1.109 lbs/ft.; ultimate tensile strength, 26,450 lbs. The mechanical tension applied to the conductors was controlled to 20% U.T.S. within 1%.

'I' insulator strings, restricted against blowback were used at the suspension points. These were connected to yoke plates that could be rotated, allowing bundle tilts of up to 20° in either direction. Suspension clamps were articulated. The central 1200 ft. span was instrumented to monitor both aeolien vibrations and wake-induced oscillations. Strain-gaged cantilever beams were mounted on each of the bottom subconductor suspension clamps. These were set up so as to detect relative conductor movement in the vertical direction at 3½ in. from the last point of contact with the clamps, in accordance with the IEEE Standard[16]. Spacer clamps were not instrumented. Piezoresistive accelerometers were used in each consecutive subspan over about one-half span. Except for one accelerometer on each bundle, all were positioned horizontally at one third of the subspan length on the southeast bottom subconductor. One accelerometer per bundle was set vertically in the second subspan from the end.

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Accelerometers were mounted on the southeast bottom subconductor because for the northwest winds prevailing at the site this subconductor lies in the wake of its upstream neighbor. Experience indicates that dowstream conductors in quad bundles show oscillations of higher amplitudes than upstream conductors.

Wind speed and direction were monitored at the top of each tower delimiting the 1200 ft. span and also at each mind-span at conductor level.

The output from each transducer was transmitted through lead wires to the test building where it was recorded on a 52 channel oscillograph according to a sampling depending on prevailing wind conditions. However, since accelerometers were used to monitor only wake-induced oscillations, their output was fed through 3 Hz cut-off frequency low pass filters prior to recording.

TEST PROGRAM

The testing program comprised five different tests. The first test was conducted during the period extending from August to December 1976. It aimed at comparing the performance of articulated damping spacers and articulated non-damping spacers in controlling either aeolian vibrations or subspan oscillations. For that purpose, a set of commercial spacer-dampers (Fig. 2a), hereafter designated as CSD, were installed on bundle #1 on both the 900 ft. span and the 1200 ft. span according to the spacings shown in table 1.

Table 1 Spacer spacings for test 1.

SPAN (ft.)	SUBSPAN LENGTHS (ft.)
900	150-190-220-190-150
1200	150-215-275-215-195-150

A second set of identical commercial spacer-dampers were modified by removing their elastomeric elements and adding nylon bushings to insure arms would pivot freely in the spacer plane without significant friction. To provide restoring capacity, the clamp end of each arm was tied to the central frame through a flexible metallic blade. Dimensions of the blade were chosen so that the tangential stiffness of the arms in the plane of the spacer was about the same as the corresponding stiffness of the CSD's. Fig. 2b shows one of the modified spacer, hereafter designated as articulated non-damping spacer or ANDS. Bundle #2 of the test line in the 900 ft. and 1200 ft. spans was then equipped with a set of ANDS with the same spacing as on bundle #1 (table 1). No Stockbridge or other type of line damper was used.

The last four tests were carried out during the period extending from February to July 1977 in the course of the development of a new spacer-damper. In this case, the aim was to establish the influence of both the spacer arm tangential stiffness and the inertia of the central frame on the bundled conductor response to aeolian and wake-induced excitation. To facilitate comparison of test results, a set of commercial spacer-dampers (same as in test No.1) were installed on bundle #1 in all three spans and these remained in place until completion of the last test. With reference to test No.1, the number of spacer-dampers and spacings were changed; the new spacing is indicated in table 2.

Table 2 Spacer spacings for tests 2 to 5.

SPAN (ft.)	SUBSPAN LENGHTS (ft.)
900	120-150-170-200-150-110
1200	135-165-190-220-190-165-135
1500	150-175-225-200-225-200-175-150

Concurrently, bundle #2 was equipped in all three spans with a set of experimental spacer-dampers,ESD (Fig. 2c). The ESD's had a distinct articulation made out of eight elastomeric cylinders (four on either side) confined within a cavity at one end of the spacer arm and a cross-shaped core tied to the central frame. One advantage of this type of articulation lies in the fact that the spacer arm stiffness can be set at any desirable value merely by changing the length of the elastomeric cylinders. Formed armor rods were used to tie the spacers to conductors. At any time during the tests, there was a one-to-one correspondence between the distribution of CSD's on bundle #1 and the distribution of ESD's on bundle #2 (table 2).

The physical characteristics of the ESD's were given four sets of values corresponding to tests No.2 to 5 (table 3).

The geometrical and physical properties of each type of spacer tested are given in table 4 along with the nomenclature suggested in figure 3. The tangential stiffnesses, k_t and structural damping factors η of the arms were determined dynamically using a laboratory test bench in the frequency range from 7 to 30 Hertz and temperature range from -40^oC to $+20^oC$. Characteristics indicated in the table, to within about 10%, are those which applied to the weather conditions at the time of testing.

TEST PROCEDURE AND DATA REDUCTION

The test procedure was based on a clear distinctions between aeolian vibration measurements and wake-

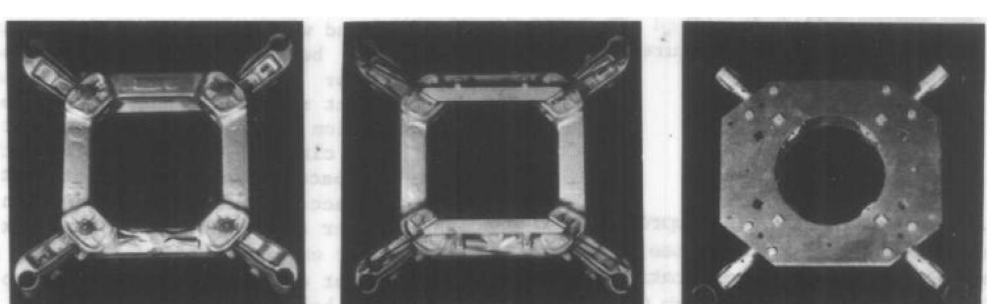

FIG. 2 Articulated spacers tested. Commercial spacer-damper, articulated non-damping spacer and experimental spacer-damper respectively.

Table 3 Combinations of articulated spacers tested. CDS: commercial spacer-dampers; ANDS: articulated non-damping spacers; ESDI: experimental spacer-dampers, Ith set of tangential stiffness and frame mass.

TEST No.	BUNDLE No.1	BUNDLE No.2
1	CSD	ANDS
2	CSD	ESD1
3	CSD	ESD2
4	CSD	ESD3
5	CSD	ESD4

Table 4 Spacer geometrical and physical characteristics.

SPACERS	CSD	ANDS	ESD1	ESD2	ESD3	ESD4
a (in.)	3.77	3.77	2.96	2.96	2.96	2.96
b (in.)	5.50	5.50	7.50	7.50	7.50	7.50
m (lbs)	2.75	2.75	1.94	1.94	1.94	1.94
M (lbs)	7.87	9.85	12.5	12.5	12.5	18.5
I_A (lbs-in.^{2})	9.9	9.9	18.8	18.8	18.8	18.8
I_F (lbs-in.^{2})	365.	4.25	479.	479.	479.	695.
k_a (lbs-in.)	750.	-	9750.	5880.	5880.	5880.
k_t (lbs-in.)	37.	30.	66.	42.	27.	42.
η	.18	-	.28	.28	.22	.28

induced oscillation measurements and observations. This can be justified on the ground that wake-induced oscillations are always absent at low wind speeds (< ~ 10 mph) while aeolian vibrations can manifest themselves severely under these conditions. Conversely, wake-induced oscillation amplitudes are significant only when the wind blows at moderate or high speeds which in turn does not favor high amplitude aeolian vibrations.

Hence, under propitious low wind speed conditions, the conductor bundles were set at zero tilt and signals from the four strain-gaged cantilever beams were displayed automatically on the oscillograph at the rate of one 5-second sampling per half hour period. The record included also the wind speed signal and the wind direction signal sensed at mid-span in the 1200 ft. span. Data was extracted from the records according to the IEEE Standard[16]. However, in addition to maximum bending amplitudes and frequencies, mean wind speed and direction were also determined. Signals corresponding to maximum bending amplitudes below 0.5 mil were rejected.

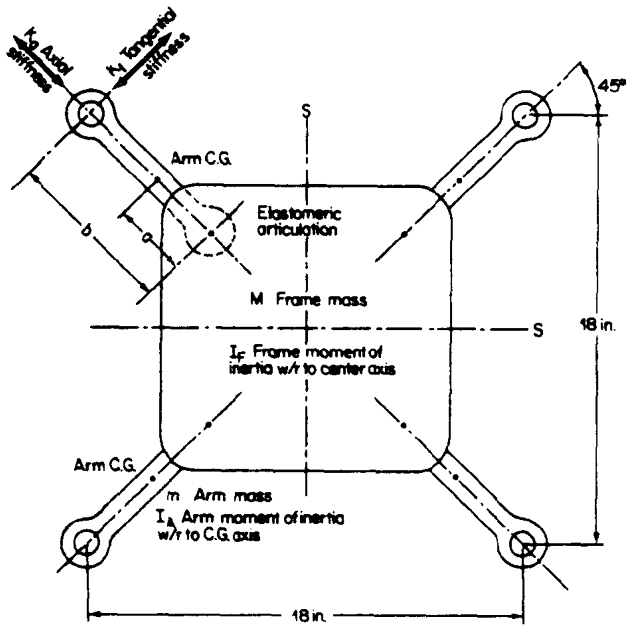

FIG. 3 Spacer geometrical and physical parameters.

Under actual or anticipated moderate or high wind conditions, the conductor bundles were systematically tilted at 10 degrees so that the dowstream conductors would lie in the lower part of the wakes from their upstream neighbors. At night and during weekends, the direction of tilt was based on the forecast from the nearby meteorological station. A number of sweeps of the bundle tilt angle through the range of 20° to -20° demonstrated that the chosen tilt angle was generally the most critical with regards to oscillations. The oscillograph was then fed with at least two wind signals and also with the signals from the accelerometers in order to detect any oscillation that could appear on either bundle. One-minute signals were recorded at the rate of one sample per half-hour period. Besides, a great number of visual observations, either direct or through the video cameras, were done during working hours. For one thing, they allowed to check coarsely the measurements of oscillation amplitudes taken by means of accelerometers.

Oscillographic oscillation records were processed in a manner fairly similar to aeolian vibration records. In this case, however, amplitudes of acceleration were converted to amplitudes of displacement each time that the signal periodicity was sufficiently well defined to allow the required computation. That was generally the case during periods of "bundle activity". Records showing less than 5 consecutive cycles of oscillation in the range .75 to 1.75 Hz were rejected. On the contrary, the oscillation was declared "sustained" when the corresponding signal exhibited an obvious periodicity over a minimum period of 40 seconds; otherwise, the oscillation was considered "unsustained". Bundle snaking events were identified by signal frequencies of about 0.3 - 0.4 Hertz indicating a two-loop mode in the central 1200 ft.-span.

AEOLIAN VIBRATION

Tables 5a and 5b show the distribution of maximum bending amplitudes at the suspension clamps of both bottom subconductors on either bundle when equipped respectively with articulated damping spacers and articulated non-damping spacers (test No.1). Each of these tables combines results of measurements on both bottom subconductors. It is to be noticed, however, that aeolian vibration amplitudes are very often higher on dowstream subconductors relatively to their upstream neighbor. This is in agreement with reference 11.

With regards to aeolian vibration control, tables 5 thus reveal very clearly the outstanding superiority of articulated spacers incorporating damping over otherwise similar spacers but without damping. Besides, table 5b indicates the range of frequencies over which extra protection is needed. The safe bending amplitude corresponding to a peak bending strain of 150 micro-inches/inch in the outerstrands of the conductor employed is equal to 7 mils peak-peak according to the IEEE empirical relationship[16]. Hence, it is seen that the non-damping spacers did not insure an adequate control of aeolian vibration in the frequency range extending from 4 to 20 Hz.

Enveloppes of maximum bending amplitudes at the suspension clamps as a function of frequency are shown in Fig. 4 for tests No. 2 to 5. Comparing first the curves obtained with the commercial spacer-dampers on bundle #1, which went through all of these tests, it is seen that results are fairly consistent on account of the fact that these enveloppes are traced through extremum values which have only a fair probability of occurence.

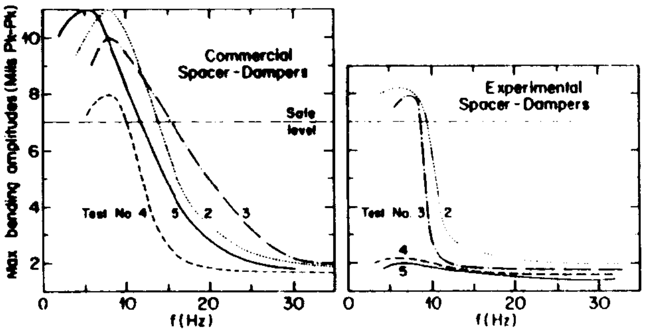

FIG. 4 Enveloppes of maximum bending amplitudes at suspension clamps. Total records: test 2: 275; test 3: 536; test 4: 306; test 5: 488.

The comparison of enveloppes resulting from tests No. 2, 3 and 4 on bundle #2 indicates an improvement in the performance of the test spacer-dampers as their articulations become more flexible. With tangential stiffnesses set at a value of 27 lbs/inch, as in test No. 4, maximum bending amplitudes at the suspension clamps did not exceed 2 mils. That result came out despite the fact that the structural damping factor of the ESD3's articulations as compared to the ESD1's or ESD2's was about 20% lower.

Test No. 5 provides an indication of the effect of the central frame mass in the control of aeolian vibrations. Indeed, maximum bending amplitudes that appeared at suspension clamps on bundle #2 when equipped with the ESD4's having exactly the same geometrical and physical characteristics as the ESD2's (table 4) except for a heavier central frame, were always below 2 mils, which is comparable to the performance achieved with the ESD3's, as just discussed. This also agrees with reference 11.

In other respects, it was possible by means of the great deal of field information available from test No. 1 to study how both the well-known Strouhal relationship and the cross-flow principle as applied to the vortex shedding phenomena are verified in the case of a practical aerial line. The Strouhal relationship relates the frequency f of the vortices shed on each side of a cylinder lying in a cross-flow to flow speed, V_n, and cylinder diameter, d:

$$f = 0.20\ V_n/d$$

while the cross-flow principle states that should the flow be yawed with respect to the cylinder, only the component normal to its axis should be accounted for.

Fig. 5 shows a curve which encloses a total of about 5800 observations of aeolian vibration frequency vs. normal component of windspeed in mid-span at conductor level. A least square straight line fit over all of these observations yields the following relation:

$$f = 0.15\ V_n/d$$

It is thus seen that the factor of proportionnality is significantly lower than the corresponding factor in the first relation. Besides, the standard deviation for f amounts to 8.7 Hz. It is interesting to notice that the scatter of the f values about the above straight line is roughly constant over the range of the normal component of mean windspeed.

Table 5 Occurences of aeolian vibration at suspension clamps in test 1 as a function of bending amplitude and frequency.

FREQUENCY (Hz)	MAX. BENDING AMPLITUDES (MILS PK-PK)																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
2																		
4	1																	
6	5	4	4		1	1												
8	3	1	1															
10	2																	
12	6																	
14	10	3																
16	5	1	1															
18	28	1																
20	37	1	1															
22	37	4																
24	55																	
26	48	1																
28	46	5																
30	56	6	1															
32	66	19																
34	64	34																
36	52	24																
38	67	37																
40	48	44																
42	33	43	1															
44	36	46	2															
46	19	51	2															
48	8	49	1															
50	13	49	2															
>50	23	251	27															

COMMERCIAL SPACER-DAMPERS

FREQUENCY (Hz)	MAX. BENDING AMPLITUDES (MILS PK-PK)																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
2																		
4	1	1													1			
6	13	16	7	4	1	5					1							
8	35	43	21	18	12	17	11	7	3	3	2	2	1					
10	14	25	21	10	5	3	5	3		1	3		2		1			
12	31	31	31	20	10	17	9	1	3	1	2							
14	33	42	40	23	13	13	5	7	3	1	3	2						
16	42	90	63	39	21	15	6	8	5	2	4	1	2				1	
18	16	23	19	8	7	2		5	2	2	2	1					1	
20	21	43	46	23	9	7	4				1							
22	19	29	8	2														
24	36	25	5	4		2	2											
26	39	34	8															
28	47	27	1	1														
30	47	25	4	1														
32	46	31	2		1													
34	38	34	3															
36	47	40	3															
38	28	42	3															
40	28	58	2															
42	25	41	2															
44	28	50	8															
46	14	40	4															
48	18	53	4															
50	6	45	17															
>50	17	235	89	4														

ARTICULATED NON-DAMPING SPACERS

When the least square fit is carried over any subset of observations corresponding to a specific range of wind yaw angles with respect to the test line, closely similar results are obtained. This confirms the applicability of the cross-flow principle.

WAKE-INDUCED OSCILLATIONS

Contrary to aeolian vibrations, there is yet no standardized method for the measurement or the observation of wake-induced oscillations. Likewise in this respect, there is no simple criterion which would serve to determine the merits of a system of spacers installed over a complete span. Some observers[3,8,9], have assessed spacer system performance according to the system "critical windspeed", i.e. the minimum windspeed for wake-induced oscillations to occur in the system. Obviously, a system with a higher "critical windspeed" would rank higher from a performance point of view. Since no account is made for the amplitudes once they occur and since "critical windspeeds" for the spacer systems tested did not differ by much (lying in any case in the range from 10 to 15 mph), the above method is not employed here.

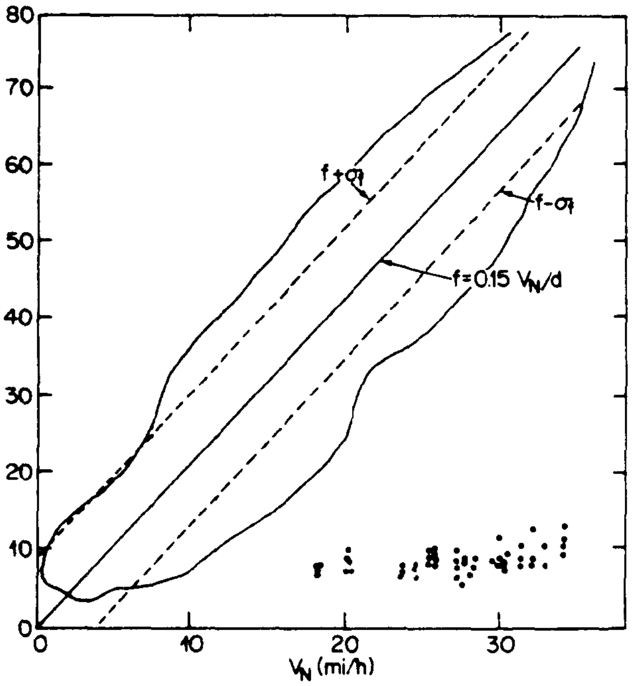

FIG. 5 Vibration frequency vs. normal component of wind speed.

Instead, spacer system performance is derated according to the potential damaging effect of wake-induced oscillations. It is first postulated, certainly not inconsistently, that damage to conductors and hardware just as conductor bending close to rigid clamps, is proportionnal to the amplitude of oscillation velocity which is the product of the displacement amplitude and the frequency. Then, a point of dismerit method is set up such that a spacer system is penalized by one point each time one subspan is seen to oscillate at a peak-to-peak amplitude of 1 in. and a frequency of 1 Hz. The total dismerit P.D. for a system over a testing period is obtained through direct summation of the points of dismerit over all instrumented subspans and over all records. This could be expressed as follows:

$$P.D. = k \sum_j (1/l_j) \sum_i N_{ij} A_i w$$

where N_{ij} designates the number of observations at amplitude level A_i in the jth instrumented subspan and w is a weighting factor which is given, somewhat arbitrarily, the value of 1. when oscillations are sustained or the value of 1/3 when they are unsustained. It has been a matter of repeated experience at the test line that predominant subspan oscillation frequencies are, to all practical purposes, inversely proportionnal to individual subspan length even in instances involving generalized subspan oscillations over all subspans. Consequently, frequency is replaced in the above expression by the quantity k/l_j where k is taken equal to 200 and l_j is the length of the jth instrumented subspan.

It should be noted at this stage that the cumulative dismerit for a given spacer system has no meaning on an absolute basis since it is a function of both wind exposure and number of observations. It is only on relative grounds that system points of dismerit have any meaning. Such is the case in the present conjuncture which involves the simultaneous observation of two spacer systems installed side by side on identically tilted conductor bundles thus being exposed to closely similar wind conditions.

Furthermore, it is obvious that the points of dismerit method, as applied here, cannot yield precise results since, for one thing, only one subconductor was instrumented in only a few corresponding subspans on each bundle. Nevertheless, the method has provided outputs which in any case agree with the test engineer's overall estimation.

Table 6 Subspan oscillation occurences in test 1 as a function of amplitude and subspan. S.: sustained oscillation; N.S.: non-sustained oscillation.

SUBSPAN	215 ft.				195 ft.				150 ft.			
BUNDLE No.	1		2		1		2		1		2	
A (in. pk-pk)	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.
$0<A\le 1.$	1	2	1	2	1	2	1	2	5	4	4	5
$1.<A\le 2.$	2	2	1	1	8	1	4	1	4	2	2	1
$2.<A\le 3.$	11	0	4	1	7	0	2	0	2	0	1	0
$3.<A\le 4.$	5	0	2	0	1	0	1	0				
$4.<A\le 5.$	1	0	0	0								
$A>5.$	1	0	1	0								
A=0.	110		122		115		124		118		122	

Table 7 Subspan oscillation occurences in test 2 as a function of amplitude and subspan. S.: sustained oscillation; N.S.: non-sustained oscillation.

SUBSPAN	220 ft.				190 ft.				165 ft.				135 ft.			
BUNDLE No.	1		2		1		2		1		2		1		2	
A (in.pk-pk)	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.
$0.<A\le .5$	0	10	1	1	0	9	0	16	0	14	3	39	7	56	10	56
$.5<A\le 1.$	1	8	3	3	0	2	1	5	5	11	5	5	7	6	14	10
$1.<A\le 2.$	1	3	7	0	3	1	2	2	0	1	6	0	0	0	7	1
$2.<A\le 3.$	1	0	3	0												
$3.<A\le 4.$	0	0	2	0												
$4.<A\le 5.$																
$A>5.$																
A=0.	156		161		131		121		149		123		104		83	

Table 8 Subspan oscillation occurences in test 3 as a function of amplitude and subspan. S.: sustained oscillation; N.S.: non-sustained oscillation.

SUBSPAN	220 ft.				190 ft.				165 ft.				135 ft.			
BUNDLE No.	1		2		1		2		1		2		1		2	
A (in.pk-pk)	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.
$0.<A\le .5$	0	3	0	2	0	5	0	13	0	24	1	47	6	68	11	69
$.5<A\le 1.$	3	6	0	9	1	12	0	20	5	38	7	41	19	33	21	38
$1.<A\le 2.$	2	16	2	21	2	10	3	6	2	22	5	14	9	12	11	12
$2.<A\le 3.$	2	7	0	1	1	0	0	0	1	0	2	0	1	0	2	1
$3.<A\le 4.$	3	0	1	0	1	0	0	0	0	0	0	0	1	0	2	0
$4.<A\le 5.$	3	0	0	0									0	0	1	0
$A>5.$	2	0	0	0									0	0	3	0
A=0.	177		187		189		178		128		102		78		55	

The results of all tests are summarized in tables 6 to 10 respectively where the number of occurences of subspan oscillations, sustained or unsustained, at a given amplitude is shown as a function of the instrumented subspans in each of two spacer systems tested simultaneously. The number of observations corresponding to stable conditions, A=0, is also given. As a matter of generality, it is seen that low amplitude subspan oscillations occur relatively often in the shortest end subspans while high amplitudes oscillations are limited to the longest subspans.

Table 9 Subspan oscillation occurences in test 4 as a function of amplitude and subspan. S.: sustained oscillation; N.S.: non-sustained oscillation.

SUBSPAN	220 ft.				190 ft.				165 ft.				135 ft.			
BUNDLE No.	1		2		1		2		1		2		1		2	
A (in. pk-pk)	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.
0.<A≤.5	0	1	0	1	0	0	0	4	0	7	0	10	3	34	2	20
.5<A≤1.	0	6	0	6	1	13	0	6	0	12	2	17	5	26	7	31
1.<A≤2.	0	12	0	9	4	12	1	14	6	25	4	26	17	27	7	23
2.<A≤3.	7	15	1	6	5	5	0	0	2	2	0	0	2	1	0	0
3.<A≤4.	2	4	0	0	1	1	0	0					0	1	0	0
4.<A≤5.	1	1	0	0												
A>5.	4	0	0	0												
A=0.	132		160		140		164		128		128		71		100	

Table 10 Subspan oscillation occurences in test 5 as a function of amplitude and subspan. S.: sustained oscillation; N.S.: non-sustained oscillation.

SUBSPAN	220 ft.				190 ft.				165 ft.				135 ft.			
BUNDLE No.	1		2		1		2		1		2		1		2	
A (in. pk-pk)	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.	S.	N.S.
0.<A≤.5	0	0	0	1	0	8	0	19	2	32	0	40	7	69	9	64
.5<A≤1.	1	12	24	10	5	14	2	22	10	41	7	36	23	23	22	16
1.<A≤2.	10	12	23	14	35	9	2	1	6	6	2	4	1	1	3	0
2.<A≤3.	8	1	7	0	5	0	0	0								
3.<A≤4.	5	0	0	0												
4.<A≤5.	1	1	0	0												
A>5.	1	0	0	0												
A=0.	119		111		94		124		73		81		46		56	

Table 11 Bundle snaking occurences.

TEST No.	BUNDLE No.1		BUNDLE No.2	
	S.	N.S.	S.	N.S.
1	25	2	4	0
2	1	0	0	0
3	8	8	2	0
4	10	0	6	2
5	0	0	0	0

Occurences of bundle snaking are given in table 11.

Now, integration of the results obtained for subspan oscillations by means of the expression defined above, leads to table 12. Hence, as far as indicated by the points of dismerit corresponding to the two spacer systems used for test No. 1, damping in articulated spacers provides no advantage in the control of subspan oscillation. In this respect, non-damping articulated spacers incorporating roughly the same tangential stiffness perform even better.

Table 12 also shows that the performance of the ESD1's with the highest tangential stiffness is definitely lower as compared to the reference CSD's. Overall performances with regards to subspan oscillation then become roughly equivalent in test No. 3 when the ESD tangential stiffness (ESD2) was set at 42 lbs/in. However, with a tangential stiffness of 27 lbs/in., the ESD3's proved to be superior to the reference CSD's. A similar result although not as pronounced, was obtained in test No. 5 while using the ESD4's having the same characteristics as the ESD2's except for a heavier central frame.

Table 12 Spacer system points of dismerit.

TEST No.	TOTAL RECORDS	P.D.(1)	P.D.(2)	P.D.(2)/P.D.(1)
1	135	111	51	0.46
2	181	30	69	2.30
3	233	133	142	1.07
4	192	161	74	0.46
5	174	157	100	0.64

All these results were generally confirmed by a number of direct visual observations of the conductor bundle behavior both in the central instrumented span and in adjacent spans.

From the last four tests, it is thus seen that a low tangential stiffness combined with an adequate central frame mass are desirable features in articulated spacer-dampers. It is interesting to note that it is so for a good control of either aeolian vibrations or subspan oscillations.

RAIN VIBRATION

Under the combined influence of rain and moderate winds, either single or bundled aerial conductors behave in a very peculiar manner[8,10]. Conductors are then seen to vibrate severely along changing paths which have their major axis at one time horizontal and at another time vertical. This type of conductor vibration has been designated rain vibration. It superposes to aeolian vibrations which are always present and also to subspan oscillations which could activate bundle conductors.

However, should propitious conditions be encountered, frequencies of each vibration phenomena are well separated. This is shown in the lower right hand part of Fig. 5 where rain vibration frequency is plotted as a function of the normal component of wind speed. Rain vibration frequencies were observed in the range from about 6 to 20 Hz. while, at the prevailing winds, aeolian vibration frequencies were much higher. A statistical test run over the rain vibration observations show that the f and V_n values are not significantly correlated.

Maximum bending amplitudes at suspension clamps due to rain vibrations are given in table 13 for tests No. 1 and 3. It is seen that rain vibrations are the cause of much higher vertical bending amplitudes than aeolian vibrations. This statement stands for any of the articulated spacers employed.

Table 13 Maximum bending amplitudes at suspension clamps due to rain vibrations.

TEST No.	MAX. BENDING AMPLITUDES (MILS PK.-PK.)	
	BUNDLE No.1	BUNDLE No.2
1	11	8
4	14	15

CONCLUSIONS

The test line studies reported herein show that damping must be incorporated in articulated flexible spacers for a proper control of aeolian vibrations. In this respect, it is also demonstrated that the performance of articulated damping spacers improves as their arm tangential stiffness gets lower or as their central frame gets heavier.

As for the attenuation of subspan oscillations, the above conclusion still applies. However, the test results indicate that damping in this regard is not beneficial. Under the same conditions of installation and exposure, articulated non-damping spacers performed even better than otherwise similar spacers but with damping capacity.

Rain vibrations induce severe dynamic bending in the subconductors at the suspension clamps. The commonly accepted safe level of amplitude was very often exceeded whenever they occured.

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TEN YEARS OF PROGRESS WITH SELF-DAMPING CONDUCTOR

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Abstract - Self-damping conductor development is outlined and the depth of the research is illustrated. The rationale of the design is explained in terms of the interference between components, the suppression of amplitude gain by depressed resonance and the reduction of wind input from lowered amplitude. Minor wind excitation remaining causes bumping of components, changing the motion to higher frequency noise which is quickly damped. Experience of many utilities with the remarkable vibration control provided by this product, particularly at high tension with resulting economy, has led to a utilization growth rate which has continued its upward trend continuously throughout the past ten years.

INTRODUCTION

Self-damping conductor*, ACSR/SD, was developed twelve years ago to control the aeolian type of vibration in overhead transmission lines. It was first described [1] to the IEEE at the 1968 Summer Power Meeting in Chicago. Several technical papers which followed were largely a duplication of material in [1] but one was entirely new material [2].

Self-damping (SD) conductors differ from conventional ACSR transmission line conductors, in that the aluminum wires are trapezoidally shaped and sized so that each aluminum layer forms a stranded tube which does not collapse onto the layer beneath when under tension, but maintains a radial gap or clearance between layers. A typical design is illustrated in Fig. 1. Sizes to about 30 mm (1.2 in.) diameter have two aluminum layers and larger sizes normally have three layers, the outer two of which may be in intimate contact with each other to provide a more stable and stronger outer shell.

The reader will be introduced to the vast amount of in-depth work which was done to develop and prove the performance of Self-Damping conductors. Various aspects of interest to users and potential users are covered supplementing laboratory work including economics and advantages of SD conductor which are sometimes overlooked. Actual conductor kilometres installed from 1968 to 1978 also are included and this is the most powerful evidence of the success of SD conductors.

RATIONALE OF DESIGN

1) The Aeolian Vibration Problem

Wind induced resonant vibration has been well documented. It will be sufficient here to note that it is a forced vibration due to the small eddy forces synchronized with a natural frequency. Amplitudes become significant only because of the state of resonance and the low damping. The eddy shedding frequency and the vibration wavelength by string theory, ignoring stiffness, are:

$$f = 0.2\ v/d \qquad (1)$$

$$\lambda = \frac{1}{f}\left(\frac{T}{m}\right)^{\frac{1}{2}} \qquad (2)$$

where

- f is frequency, hertz
- v is wind velocity perpendicular to the conductor, metre per second
- d is diameter, metre
- λ is wavelength (i.e. two loop lengths), metre
- T is tension, newton
- m is mass per unit length, kilogram per metre

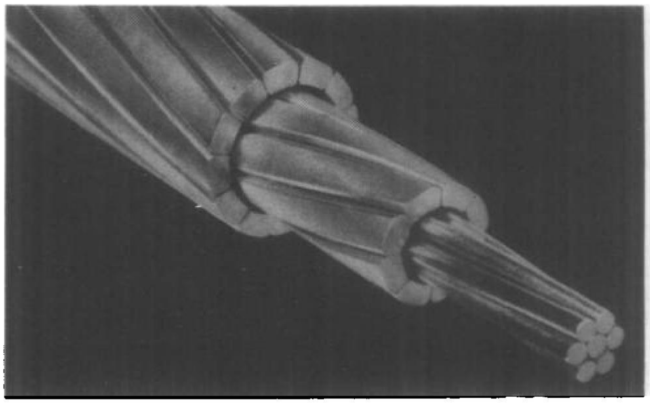

Fig. 1 A typical SD conductor

2) Mismatched Components of SD Conductors

In forced vibration tests of conventional ACSR it was evident that, with the driver force maintained constant and the frequency swept slowly in search of resonance, there was no significant vibration produced until a resonance was reached, then the amplitude peaked dramatically and the standing waves were sharply defined. It was obvious that if resonance could be avoided then wind forces could cause no trouble.

It was reasoned that if a line conductor could be constructed with internal gaps separating it into several components, as in Fig. 1, then it would be most unlikely that the components would have similar resonant frequencies. Wind forces would find a resonance of the outer layer but if the inner layers could not respond precisely to the same frequency they would remain still and inhibit motion of the outer layer. The very first sample which was fabricated showed that vibration control had been achieved.

Experiments in which the tension in the components could be adjusted separately, revealed that when components were adjusted to have the same T/m ratio they then had the same loop length at the same frequency (2) and could move in harmony and were nearly as excitable

* Patented by Alcan. Patent Nos.: USA 3,445,586, Can. 844,176, USA 3,378,631. SD conductors are also made by Alcoa and others under licence agreements.

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as ACSR. The normal state of the tension, however, is such that each component has a significantly different T/m ratio, hence a different loop length for the same frequency or conversely, if constrained to move with the same loop length, then they have different resonant frequencies (2). For one component to vibrate significantly at its resonance it has to force another component to move along with it when that component is not at resonance which is not practical.

As an example, tensioning the core of Drake/SD separately (the two aluminum layers tensioned as a unit) it was found that at 30% RTS and equal stretch of the steel and aluminum, the T/m ratio of the aluminum was typically about 0.35 T/m of the steel core. This corresponds to a strain in the steel of about 0.18% and in the aluminum of 0.08%, giving a degree of preload to the steel core essentially the same as for conventional ACSR. In both types of conductor this difference is caused by creep during preloading, radial compression under tension and differences in lay length of the different layers. (It may also be influenced in a short test length by a springiness and initial low modulus which makes the length at zero stress uncertain).

It should be emphasized that the primary mechanism of SD conductor performance is precisely this inability of the different components to resonate at a common wavelength and frequency so that some part is always definitely not in resonance. This prevents resonant amplitude growth of the whole assembly. There is also some dissipation of vibration energy by friction damping but this is deemed to be a secondardary effect in this type of conductor.

3) Damping Mechanisms

The interference of the inner layers with the wind induced motions of the outer layer, produces two powerful damping mechanisms acting upon the limited motions which are possible.

One of these is the bumping against the inner components which produces a small force opposing the motion, destroying to some extent the smooth harmonic interchange of energy from the kinetic to potential to kinetic states, which is a basic requirement for the amplitude gain known as a resonant amplification.

Secondly, the bumping and rubbing together of components produces some noise and heat. The noise is evidence that the low frequency aeolian vibrations have some of their energy changed into higher frequency (audible) vibrations in the metal and in the air. This mechanism is the one minor part of the several vibration control mechanisms which truly dissipates energy and is therefore damping in the usual meaning of that word. It is not practical to describe SD conductor by mathematical expressions because of these several involved mechanisms of amplitude control.

4) Restricted Driving Force

Another important factor is that by limiting outer layer vibrations to low amplitude nonharmonic motion the force input from the wind is very restricted and very little damping is required.

The magnitude of the driving force from the wind, as a function of the amplitude/diameter ratio (Y/d), has a trend rising from virtually zero almost linearly to reach a maximum.[3] This result is at variance with what some investigators have assumed on theoretical grounds, i.e. that the force has a high value even at zero amplitude. Reference [3] explains that the increase in force is not due to the variation in the amplitude of the wake but depends on the change in the phenomenon as the amplitude increases. At small amplitudes the phenomenon is not two dimensional but three dimensional with random characteristics. Consequently the lift force is low. It is not until the amplitudes increase significantly, relative to the diameter, that the eddies lose their random nature and the vortex force increases. This point was tested by Koppmann [4]. who photographed the slipstream and found that only above certain amplitudes does the slipstream change from a three-dimensional to two-dimensional form.

5) High Damping of the Outer Layer

It has long been recognized that the aluminum layers of ACSR are stressed less highly than the steel core due to creep, shorter lay length and bedding in. This has been confirmed in tests of SD conductors as well in which tension in individual layers was measured.

In the Drake/SD sample discussed in item 2 above, the aluminum layers averaged 27% of their rated strength while the core was at 30% of its rated strength. Larger differences between aluminum and steel stressing are expected in larger conductors.

A lower tension in the outer components has no beneficial effect in conventional ACSR because the vibration performance is governed by the total tension. In SD conductors the damping performance would be expected to be influenced by a lower tension of the outer layers since they act independently of the total tension. It has been found that the damping of an outer layer of SD conductor, (with the core and inner layer removed entirely) tested at 30% RTS, is similar to that of conventional ACSR of the same size at 30% tension. In both cases damping improved by a factor of about 1.6 when the tension was lowered to 20% and by a factor of 3.5 at 10%.

This improved damping of the outer layer of SD conductor as a result of stress distribution is not significant at the diameter of Drake/SD but would be expected to make a significant contribution to the performance of large sizes. This helps to explain why the performance of SD conductors appears to be independent of size in spite of eddy forces being proportional to diameter. On the other hand it is also possible that the amplitude cannot get large enough nor the motion smooth enough to stabilize the random forces from the wind [3]. The relative importance of each of the various vibration control mechanisms which are present has not been established since they cannot be segregated.

TEST FACILITIES EMPLOYED DURING DEVELOPMENT

1) Laboratory

(a) Indoor 52 m (170 ft) Spans: A conductor damping test facility was put into operation at the Alcan Kingston Research Centre early in 1967 with a space of 58 m (190 ft) between end frames. Considerable care was taken in the design to provide rigid terminals with concrete piers tied to bedrock. Concrete reflector blocks measuring 1 m^3, having large metal clamping blocks defined the actual test span at 52 m (170ft). The eight large bolts per clamp were tightened securely by impact wrench after some hours of preloading and final tension adjustment of the conductor. The clamping blocks had oval grooves in the various sizes of inserts to ensure gripping of the core in the case of SD conductors.

The electromagnetic driver was positioned precisely at mid span and was excited by using a sine wave generator. The frequency of excitation was adjusted so that the force was in phase with the velocity at natural frequencies of the span. Where velocity was not sinusoidal, as in SD conductor tests, the frequency tuning was done by adjusting for maximum velocity. The driver force was adjusted to 3.34 N (0.75 lb) rms before recording the velocity. The force was selected as the maximum which would permit the testing of SD conductors at a frequency as low as 5 Hz without tripping the safety switch on the driver set at approximately 10 mm. This level of excitation was remarkably similar to the peak levels of wind excitation over the frequency range of interest. The voltmeters used to read force (current to the driver) and voltage from the velocity coil were designed to read rms voltage, accurate to 3%, down to 5 Hz.

Damping studies had not reached the stage where methods or units were standardized. Damping may be defined as energy lost per unit volume, or per total energy, or as the sharpness of the resonant peak, etc.

The choice of method was based on the equation for forced vibrations with viscous damping; e.g., Den Hartog [5]. The first term, mass times acceleration, is

$$m\ddot{x} + c\dot{x} + kx = P_o \sin\omega t \qquad (3)$$

the inertia force, the damping coefficient c times the velocity is the damping force, k is the spring stiffness and kx is the spring force. These three must be in balance with the input force $P = P_o \sin\omega t$ having a circular frequency of ω. When a steady state of vibration has been reached and the force P has been adjusted to be in phase with velocity, then the acceleration and spring forces are equal and opposite, peaking at the maximum displacement. The force input P just equals the force due to damping $c\dot{x}$ and the damping coefficient c equals P/velocity. If the damping is proportional to velocity (viscous damping) as in a dash pot, the c is constant and independent of frequency, but damping also includes friction which is independent of velocity and air drag which varies as velocity squared. The coefficient c is therefore usually shown as a variable plotted against frequency. This coefficient, c, is often referred to as Z the mechanical impedance, thus, changing only the symbols:

$$Z = F/vS \qquad (4)$$

Z = mechanical impedance per unit length (damping), newton second per metre squared ($lb.s.ft^{-2}$)

F = force (rms), newton (lb.)

v = velocity (rms), metre per second ($ft.s^{-1}$)

S = span, metre (ft)

(b) Wind Excitation - Outdoor Spans: The test site is located 33 km west of Kingston on a plateau of open pasture on the shore of Lake Ontario at an elevation of about 12 m (40 ft) above the lake. The direction of the line is north-south. Prevailing winds are from the south-west and west about 60% of the time. Three two-pole H-frame structures were provided with double wooden crossarms accommodating three horizontal parallel conductors 10.7 m (35 ft) above ground level with two spans of 198 m (650 ft) each.

Conductor vibration at a distance of 90 mm (3½ in.) from the last point of contact with the suspension clamp was detected by strain-gauged cantilever type sensors with flexural stiffness characteristics equivalent to those of Ontario Hydro Live Line Recorders*. The three conductor vibrations as well as wind speed, wind direction and ambient temperature were simultaneously recorded. Record analysis was done in accordance with IEEE paper No. 65-156 entitled, "Standardization of Conductor Vibration Measurements"[6].

(c) Stringing Trials - A One Mile Test Facility: Although the initial experiements in stringing SD conductor were done with the assistance of Ontario Hydro near Toronto, it was more practical to have a facility close at hand. A suitable site was found at the Alcan Kingston Research Centre and five poles were erected at 274 m (900 ft) centres. Anchors were provided at 173 m (450 ft) beyond the outer poles.

Some conductors were passed around a neoprene lined stringing sheave 500 mm (20 in.) diameter at the end of the line and doubled back to evaluate any tendency for looseness to accumulate after pulling out 2740 m (9000 ft) and also to show that the SD conductors could stand up well to the severe bending under load. Various methods of gripping the three components at the forward end were checked.

A field engineer, Mr. J.P. McGoey, acted in an advisory capacity to assist utilities in their early experiments with SD conductors, thus considerable experience was brought together in a relatively short period.

2) Field Tests

As a supplement to laboratory tests the SD conductor evaluation programme was augmented by various test installations in Canada and the United States. In the USA, test conductors were installed in lines of Northern States Power, Oklahoma Gas and Electric, and Tennessee Valley Authority. In Canada, test installations were made in lines of Ontario Hydro, Manitoba Hydro and Calgary Power. Evaluations in the field were made using the Ontario Hydro Live Line Recorders and HILDA (manufactured by SED Systems Limited, Saskatoon. It also meets requirements of IEEE standard method of vibration measurements). The cooperation of the Utilities involved in these test lines is appreciated and the results obtained were invaluable in the assessment programme.

TEST RESULTS

1) Laboratory Test Results

(a) Indoor

(1) Damping Tests: The damping per unit length of conventional ACSR is illustrated in Fig. 2 for the 795 kcmil size. The outstanding feature is the serious loss of damping of conventional conductors as tension is increased. The damping of the same size of SD conductor is shown in Fig. 3. Damping of SD conductors is practically independent of tension and typically it is better by a factor of 5 or more than that of the conventional conductor, when the latter is at 20% RTS.

(2) Tension Distribution Between Components: If two components of an SD Conductor have precisely the

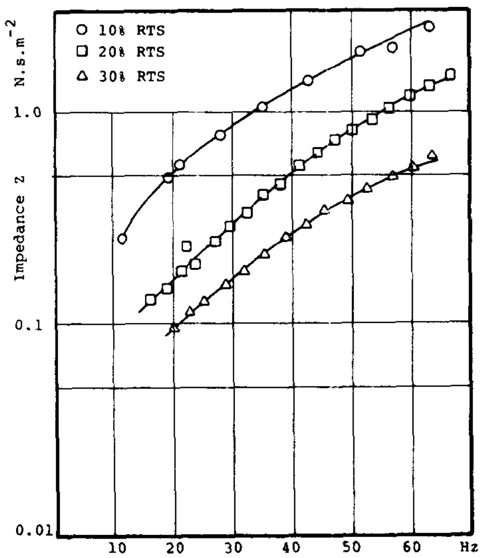

Fig. 2. Damping of 795 kcmil conventional ACSR Drake, Tern, Macaw.*

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* General Instrument Company, Toronto, Ontario, Canada. That recorder meets the requirements recommended in IEEE Paper No. 65-156.

* Code names imply conventional conductors unless SD, for self-damping, is indicated.

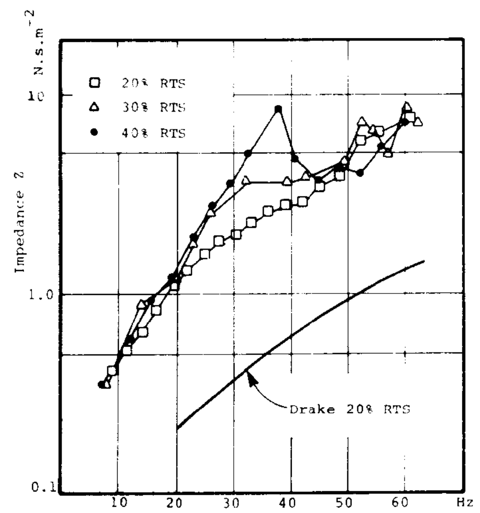

Fig. 3. Damping of Drake/SD Compared With Conventional Drake at 20%

same loop length or the same T/m ratio (2) they can move in harmony and do not provide the required vibration control. This is a critical condition for small conductors which follow string theory and occurs when:

$$\frac{\text{outer component T/m}}{\text{inner component T/m}} = 1$$

For brevity this ratio of ratios may be identified as the "P/W factor" using the old symbols for average tension and weight per unit length, hence by definition:

$$\text{"P/W factor"} = \frac{\text{T/m outer}}{\text{T/m inner}} \qquad (5)$$

Since the major mismatch is between aluminum and steel components and in most tests where component tensions were measured, the two aluminum layers were tensioned as an assembly with one load reading, P/W factors quoted refer to average T/m of the two aluminum layers divided by T/m of the steel core.

Many tests were undertaken to explore the effect of varying the tension in the components and particularly the relative tensions of the aluminum and steel. Drake/SD for example, prestressed at 35% RTS and tested at 30%, with equal lengths of components marked before tensioning and these marks kept in registry at tension, has a little less tension in the aluminum than in the steel in the ratio of about 0.8 with a resultant P/W of 0.36 and excellent damping. Although the lengths were kept in registry and thus nominally at equal strain, a calculation of the elastic strain from the known stresses (27.4 % RTS aluminum, 32.4% RTS steel) and moduli $55\text{x}10^6$ kPa and $186\text{x}10^6$ kPa ($8\text{x}10^6$ and $27\text{x}10^6$ psi), shows that the aluminum was elastically strained less than half as much as the steel, the balance of the displacement being due to creep and other effects which result in some preloading of the core, in the final stress strain curve, before the aluminum accepts loading.

Lowering the tension of the aluminum more than that of the steel (as in the case of overheating) has no detrimental effect on the damping performance, the P/W ratio being low. When the aluminum has twice as much tension as the core, such as could occur with a low steel content conductor at very low temperatures, the P/W ratio could be as high as 0.9, very close to the critical P/W for this size of conductor. When tested under this condition the damping is appreciably lowered but remains 2.5 times better than Drake at 20% RTS. Since this stress distribution only occurs at about -40 C, there would not likely be any wind problems and the damping would remain more than adequate. In the tests in which many small adjustments were made in the tension to search for minimum damping it was found that the tuning was quite critical. Only a small mismatch is required to obtain good damping.

(3) Diameter Effects: In the course of testing a range of sizes of SD conductors, it became apparent that in the frequency range of interest (5 to 70 Hz) the damping varied in proportion to the diameter. Since wind forces also vary with diameter the performance should be independent of size. This was not evaluated by the wind tests, which were limited in range, but field experience indicates that diameter has little effect.

Another diameter effect is the increase in stiffness with diameter which increases the loop length significantly in the frequency range of interest for diameters larger than 20 mm (0.75 in.). There was concern initially that this might place large SD conductors in a critical range of P/W resulting in poor damping. When the relative tension of components was better understood however this possibility of poor damping arising appeared unlikely. Very briefly the analysis, prepared by Dr. V.I. Johannes at the Alcan Kingston Research Centre, may be summarized as follows: For small conductors, minimum damping occurs when the wavelength ratio is unity (2) and (5). A more accurate model is obtained by introducing the stiffness which gives the following governing differential equation, where y_x signifies the partial differentiation with respect to x:

$$EIy_{xxxx} + Ty_{xx} + my_{tt} = o \qquad (6)$$

This equation has the general solution

$$y = \sum_{n=1}^{\infty} (A_{1_n} \cosh\alpha_{1_n} x + A_{2_n} \sinh\alpha_{1_n} x + A_{3_n} \cosh\alpha_{2_n} x + A_{4_n} \sinh\alpha_{2_n} x) e^{i\omega_n t} \qquad (7)$$

where α_1 and α_2 are the positive roots of

$$\alpha^2 = \frac{T}{2\,EI} \pm \left(\left(\frac{T}{2\,EI}\right)^2 + \frac{\omega^2 m}{EI} \right)^{1/2} \qquad (8)$$

For the case of a simply supported cable, the condition of zero displacement and zero moment at the ends is expressed by the boundary conditions:

$$y = y_{xx} = 0 \text{ at } x = 0 \text{ and } x = L \qquad (9)$$

The only non-trivial solution gives

$$\sinh \alpha_2 L = 0 \qquad (10)$$

which is satisfied by

$$\alpha_2 = \frac{i\pi n}{L} \qquad (11)$$

substitution for α in (8) gives

$$-\frac{n^2 \pi^2}{L^2} = \frac{T}{2\,EI} \pm \left(\left(\frac{T}{2\,EI}\right)^2 + \left(\frac{4\pi^2 f^2 m}{EI}\right) \right)^{1/2} \qquad (12)$$

Noting that the wavelength is given by $\lambda = 2/Ln$, a measure of the error in wavelength determination by the string equation is obtained from (2) and (12)

$$\frac{\lambda^2_{string}}{\lambda^2_{stiff}} = \frac{2}{a} \left(-1 + (1 + a) \right)^{\frac{1}{2}} \qquad (13)$$

where $a = \frac{16 \pi^2 f^2 EIm}{T^2}$

E = tension modulus of the component, pascal
I = second moment of area, metre to the fourth power

One problem in using this equation is defining the stiffness EI. The modulus E is available from tensile tests, but the value of second moment of area I can conceivably vary from that for a solid piece of material of the same cross section down to that of the sum of the individual wire I's. To determine what would be a good estimate for this value, the outer layer of a Drake/SD conductor was vibrated in the indoor span and the wave lengths at various frequencies were measured. Because of the clamped ends of the conductor, end loops were considerably longer than those in the span, and both were recorded. To permit comparison with theory, equation (6) was also solved for the case of fixed-fixed end conditions. The results for in-span loops at one tension are tabulated in Table I to illustrate close agreement between measured values and string theory with stiffness. The moment of inertia used in these calculations was that for a solid tube of equal cross section, and the good correlation confirms that this is a reasonable estimate of the layer stiffness in the cases of tensioned layers of trapezoidal wires in SD conductor.

TABLE I
Measured and Calculated Loop Lengths of Drake/SD Outer Layer at Tension 10 052 N (2260 lb)
(O.D. 28.1 mm (1.108 in.))
(I.D. 21.1 mm (0.830 in.))

	Loop Lengths in Span (m)		
Hz	Measured	String Theory	Theory with Stiffness
11.6	5.74	5.26	5.38
19.6	3.43	3.10	3.28
28	2.46	2.13	2.41
37.2	1.91	1.63	1.91
44	1.65	1.40	1.68

To illustrate the magnitude of this effect, the critical P/W ratio (13) for the outer layer is calculated and plotted in Fig. 4 against frequency with the tension stress as a parameter, for two sizes of SD conductor.

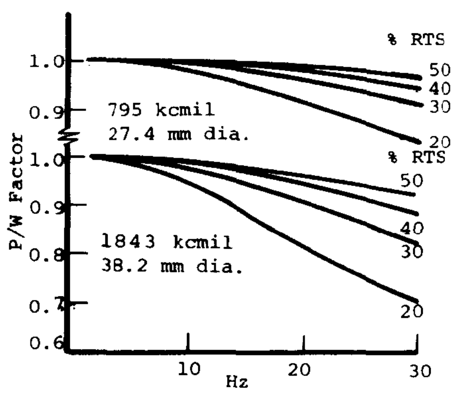

Fig. 4. Bending stiffness modifier of the critical t/m ratio for two sizes of SD.

1. Drake/SD with O.D. = 27.41 mm, I.D. = 20.3 mm and modulus assumed 52 000 MPa (7500 ksi).
2. 1843 kcmil with O.D. = 38.15 mm, I.D. = 29.24 mm and modulus assumed 40 000 MPa (5800 ksi).

Since the moment of inertia of a layer varies as the third power of the diameter x layer thickness, only the outer layer is significant.

It is perhaps a fortunate circumstance that as this stiffness effect tends to bring the loop length of the components closer together for larger diameters, the lower tension modulus due to the relatively shorter lay length of the larger diameter conductor has the opposite effect. Hence large sizes of SD conductor are as effective as smaller sizes.

(4) Gap Size: The effect of gap size on the damping performance is illustrated by Fig. 5 where the damping of Drake (plotted at zero gap) is compared with that of a variety of SD conductors fabricated with a range of nominal gap sizes.

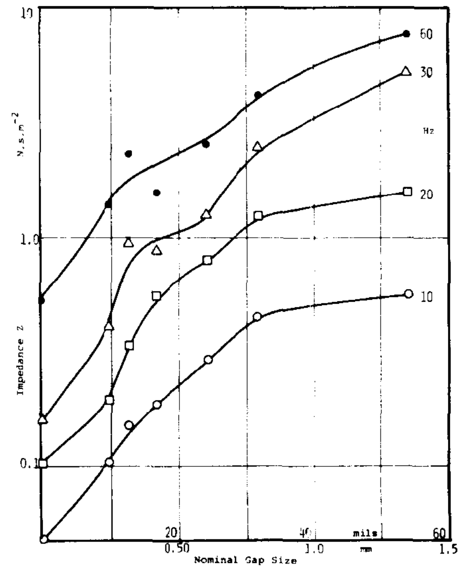

Fig. 5. Damping vs. inner gap size for 795 and 954 kcmil SD conductors at 30% RTS.

There appears to be little justification for using a gap larger than 0.76 mm (0.030 in.). Excessive gap size tends to lead to ovality of the outer layer and a less stable conductor. On the other hand even 0.76 mm (0.030 in.) appeared to be excessive for small conductors so that a nominal gap of 0.64 mm (0.025 in.) was used for small designs. These gap sizes seem to be optimum when fabrication, stringing and damping are considered collectively.

In the course of evaluating the performance of different production runs, damping tests were done on SD conductors of 795 kcmil in the range of types* from 5 to 16. Their damping performance is shown versus the mass ratio of the two inner components to the outer layer in Fig. 6 with frequency from 10 to 60 Hz as a parameter. Conductor type is also shown along with the mass ratio scale. It is evident that in the higher frequencies there is some minor lowering of performance in the region of types 5 and 7 but it is not significant. It also appears, particularly at 40% RTS and at frequencies above 30 Hz, that there could be an optimum where the combined mass of the two inner components equals the mass of the outer layer, which would occur at about type 10, but the variation in performance with weight

* Type is the ratio of the areas of steel and aluminum expressed as a percent.

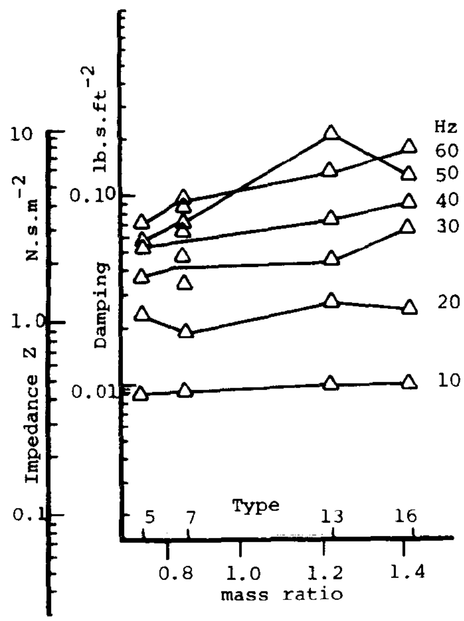

Fig. 6. Damping vs. type or mass ratio of outer layer to sum of inner components. Tension 30%.

is so very minor that the core size should be selected for other reasons. The ratio, outer layer versus two inner components, was selected for the plot because with slack cores there was optimum performance when these were equal.

It is known from the tests that an aluminum core should be avoided and the composite cores of aluminum and steel may also lead to problems without special care in design and fabrication. The present lower limit has been arbitrarily set at type 4 since there does not appear to be any merit in risking a lower steel content.

(5) Gaps Filled With Water: There was initially some concern that the performance of SD conductors could be influenced by rain water filling the gaps. To evaluate this possibility, holes were drilled at both ends of the span and water was pumped in until the gaps were filled. The damping performance did not change significantly; it was, if anything, better when filled with water. (The performance with 0.25 mm (10 mils) radial thickness of grease was also excellent.) It was noted that it took many days for the water to finally leak out of the sample indicating a degree of water tightness unlike normal ACSR where radial pressure prevents the tight closing of the layers.

(6) Corrosion Resistance: This water tightness of SD conductors was again demonstrated by a corrosion test. There was no change in the damping performance of a Drake/SD after a period of 67 days of being sprayed (saturated) twice daily from a garden sprayer with a corrosive solution. At the end of the test period the outside was heavily encrusted with salt but internally there was no evidence of corrosion. The conventional Drake sample on the other hand showed considerable attack of the inner layer and of the core.

The corrosion schedule was as follows: For 21 days the sample was sprayed once a day with 5% sodium chloride plus 0.06% glacial acetic acid giving a pH of 2.65. Since corrosion was insignificant the rate was increased to twice daily for 10 days. The sample was then degreased (because there was no significant corrosion even on the outside) and spraying continued twice daily for 15 days. Copper was then added to the solution; 5% NaCl + 0.05% glacial acetic acid + 5.41 gm copper chloride per 20.5 litres. Spraying was continued twice daily for 22 days.

(7) Span Termination: In order to determine whether or not a significant amount of damping being measured in tests resulted from conductor bending at the rigidly clamped terminations, a test was performed with Drake/SD using biaxial knife edges located at each end between the reflector block and the specimen compression fitting. The damping performance remained within the narrow scatter band for different samples of the same conductor design and it was concluded that the effect of bending at the ends of the span was not a significant factor. This test strengthened the conviction that the damping performance resulted from the interference principle and that any energy dissipation due to friction between trapezoidal wires in a layer was insignificant.

(b) Outdoor: The peak vibration amplitudes of Drake/SD in the wind are plotted against frequency in Fig. 7. These results are quite typical of the performance of other SD conductors evaluated. The performance of conventional Drake is shown for comparison in Fig.8. A smooth curve is shown on each graph to show the excitation level of the indoor tests as well.

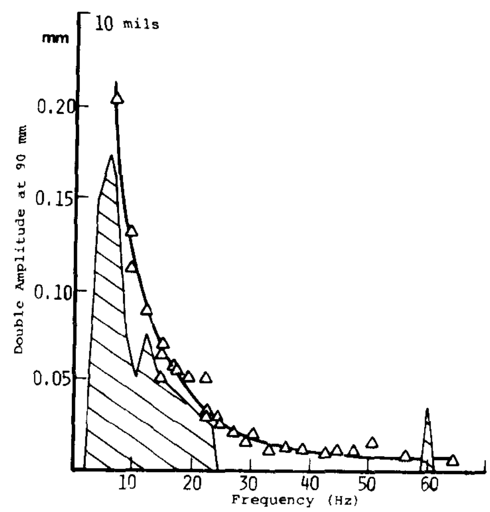

Fig. 7. Comparison of vibration levels in the wind and indoor test. Drake/SD 20% RTS

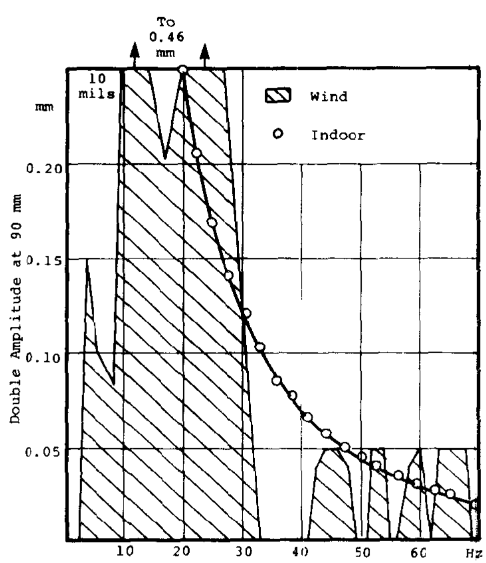

Fig. 8. Comparison of vibration levels in the wind and indoor test. Drake 20% RTS

IEEE paper 31 CP65-156 proposes tentatively that a bending strain of 150 micro strain peak to peak is safe and that 300 may possibly lead to some fatigue in 30 years in a 795 kcmil 54/7 ACSR with wire diameter of 3.08 mm (0.1214 in.). For Drake wire size these limits translate into 0.10 to 0.20 mm or 4 to 8 mils deflection at 90 mm from the clamp so that the 0.46 mm peaks recorded for conventional Drake ACSR must certainly be damaging. The Drake/SD which has less thickness (in the direction of bending) would have corresponding safe limits in the range 0.12 to 0.24 mm or 4.8 to 9.6 mils if it were being excited throughout a similar frequency range and as continuously as Drake. Its peak at 0.17 mm should be safe even if it occurred at 20 to 30 Hz with the vast number of cycles at which Drake vibrates, but since it only reached 0.17 mm in one recording period in several weeks of recording it is extremely safe.

In Fig. 9 the maximum field test vibration amplitude of three types of 795 kcmil ACSR are compared with six variations of the same size of SD conductors with % RTS as the other variable. It is clear that the performance of the SD conductors is practically independent of the tension. There is some difference in performance depending on the gap size and as indicated by the results in Fig. 9 and substantiated by other tests, the optimum gap size is in the range 0.64 to 0.76 mm (0.025 to 0.030 in.).

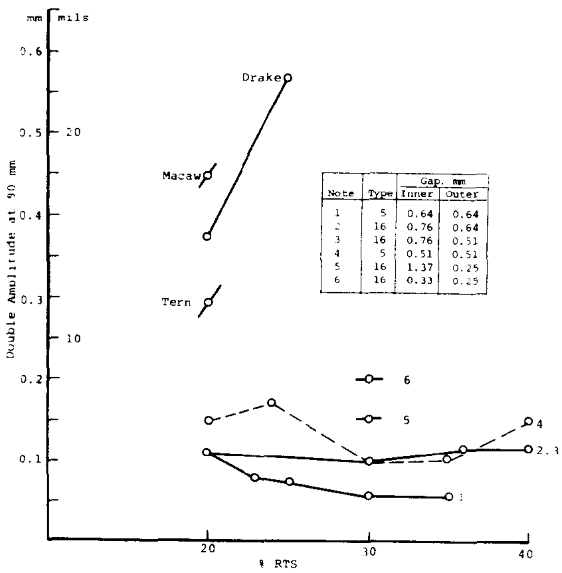

Fig. 9. Maximum outdoor vibration in 795 kcmil ACSR and SD conductors at various tensions.

(c) Stringing: In the stringing trials a number of important points were established:

(1) The core must be gripped at the forward end so that it cannot retract and before cutting the back end a clamp must be applied for the same reason.

(2) It was shown that SD conductors are equally suitable for either slack stringing or tension stringing.

(3) It was shown that special oval grooves were required in book type clamps in order to grip the core.

(4) SD conductors 20 mm diameter could be taken 180° around a stringing sheave 500 mm (20 in.) diameter without damage or permanent deformation.

(2) Observations on Installed Lines

Results of early tests were reported [1]. Considerable data was collected from service lines after 1968. These were from conductors which varied in size from 266.8 to 2680 kcmil and in Type from 4 to 23. Unloaded tensions in the conductors varied between 15 and 50% of the rated strength while temperatures of exposure during measurements varied from -40 to 50°C. For small to medium size SD conductors, typically the maximum double amplitude of vibration varied from 0.08 to 0.16 mm, (3-6 mils), using the standard 90 mm distance from the clamp mouth measuring point, at a frequency between 5 and 8 Hz. For large SD conductor sizes, the typical maximum double amplitude was 0.1 to 0.2 mm (4 - 8 mils) at 6 to 9 Hz. The incidence of conductor vibration amplitudes as large as those mentioned was very low. Valuations of the megacycle days in the records showed these to be negligible.

In early stages of service evaluation there was great interest in many vibration recordings over long periods of time. Since amplitudes of vibration in these recordings were consistently low the interest of utility companies waned with the result that most installations are checked for performance by only a few records during the expected critical times for vibrations.

ECONOMICS OF SD CONDUCTORS

Since the harmful effects of aeolian vibrations are eliminated by SD conductors, there is no longer a need to limit unloaded SD conductor tensions nor to use costly vibration damping systems to control aeolian vibrations. It has been proven in several installations of considerable length that unloaded tensions can be raised safely by using SD conductors. In fact, several lines in Canada have been designed using only two limiting tension conditions. These conditions are the initial unloaded tension at the minimum temperature and the tension under maximum design load. The level of tension at these two conditions is governed by the line safety factor and can be 50% to 60% of the conductor rated breaking strength at the option of the line designer. No attempt is made here to advocate infringement of applicable and existing code limitations. It is time however, that code limitations were examined to recognize the capabilities of SD conductors. We can no longer in conscience ignore this breakthrough in technology.

The implication of raising conductor unloaded tension or reducing conductor unloaded sags is immediately evident. A good deal of advantage can be realized by raising unloaded tensions even to existing code limits. Decreased sags can have startling results on overall line costs especially in the area of structure costs in terms of numbers or heights of structures and in reduced conductor spacings. In addition, vibration dampers and/or even more costly spacer dampers are unnecessary.

As more and more line designers take advantage of SD conductors the savings which can be realized become evident. To be fully cost effective, the decision to use SD conductor must be taken before structures are designed. Comparisons with line designs using conventional conductors at reduced tensions, necessitated by aeolian vibration control, will almost without exception show attractive economic advantages for the use of SD conductors. The exception to this would be where unloaded tensions and loaded tensions were already at their respective maximums without harmful or potentially harmful effects of aeolian vibrations.

USERS OF SD CONDUCTOR

The use of SD conductor is increasing very rapidly as shown in Fig. 10 and its potential is equal to replacement of perhaps as much as 50% or more of the ACSR being used. During the past 10 years SD conductor has been popular in areas where conventional conductors suffer most from the harmful effects of aeolian vibrations. These areas are in flat regions void, or nearly so, of vegetation of height comparable to conductor height, and in areas where steady winds blow a large portion of the time. River and lake crossings have