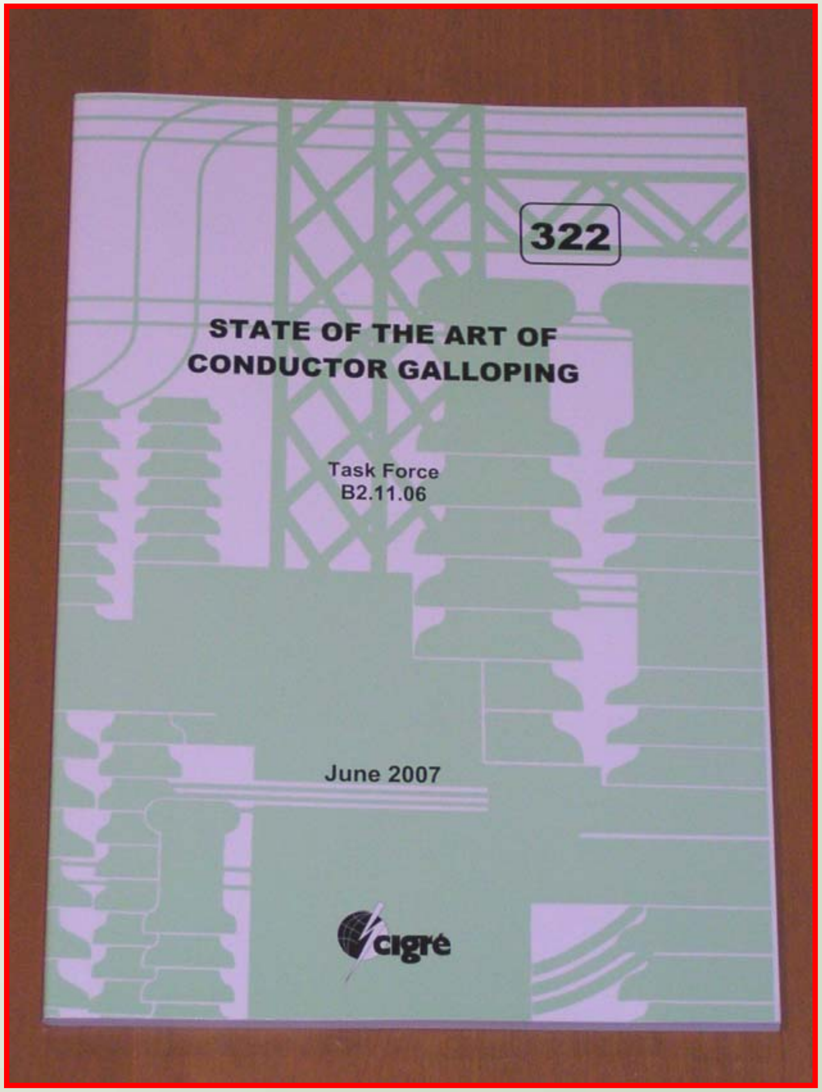
CONDUCTOR GALLOPING

A TUTORIAL PRESENTED AT THE IEEE ESMOL and TP&C MEETING LAS VEGAS, JANUARY 2008

by D.G. HAVARD

EXPANDED VERSION OF A TUTORIAL ORIGINALLY PRESENTED AT CIGRÉ B2 MEETING HELSINKI, FINLAND, JULY 2007

by J-L. LILIEN & D.G. HAVARD



TUTORIAL IS BASED ON CIGRÉ TECHNICAL BROCHURE NO. 322

"STATE OF THE ART OF CONDUCTOR GALLOPING"

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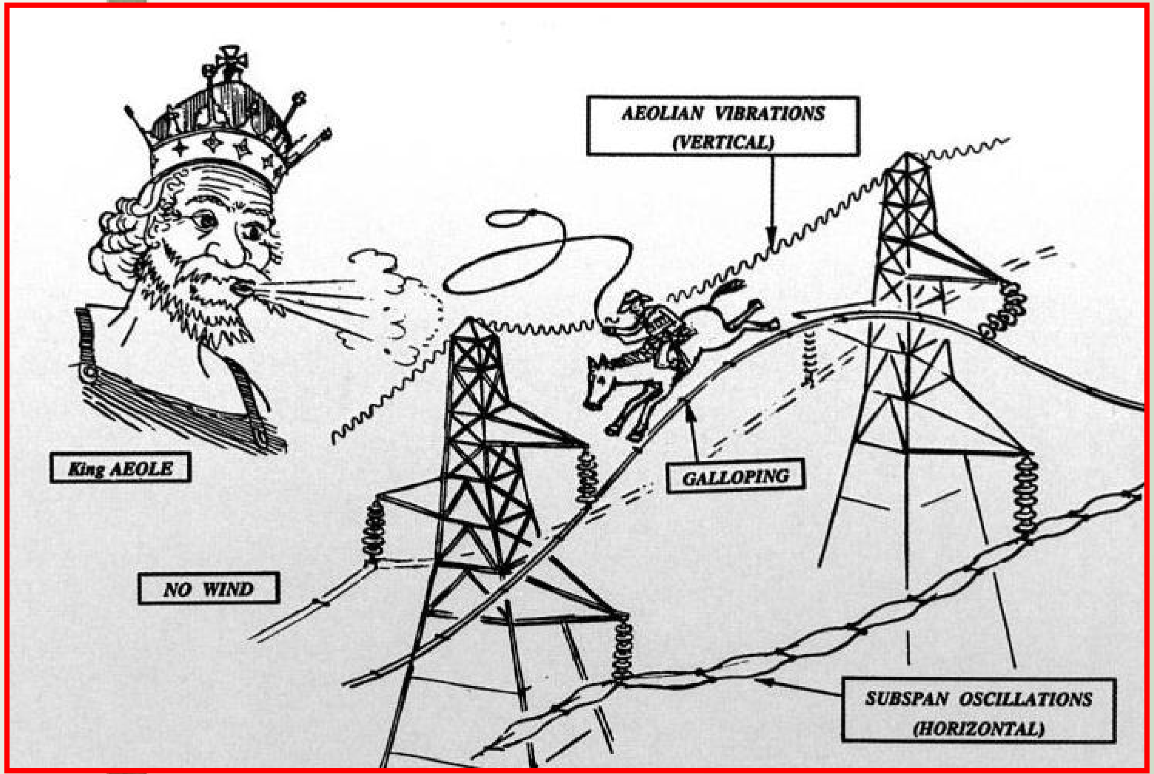
OUTLINE OF THE TUTORIAL

- *WHAT IS GALLOPING?*
- *CONDITIONS FOR GALLOPING*
- *VIDEOS OF GALLOPING*
- *MECHANICS OF GALLOPING*
- *DAMAGE DUE TO GALLOPING DYNAMIC LOADS DUE TO GALLOPING*
- *CONTROL OF GALLOPING*
- *FIELD DATA ON EFFECTIVENESS OF CONTROLS*
- *DESIGN CLEARANCES TO AVOID CLASHING DURING GALLOPING*
- *CONCLUSIONS*

WHAT IS GALLOPING?

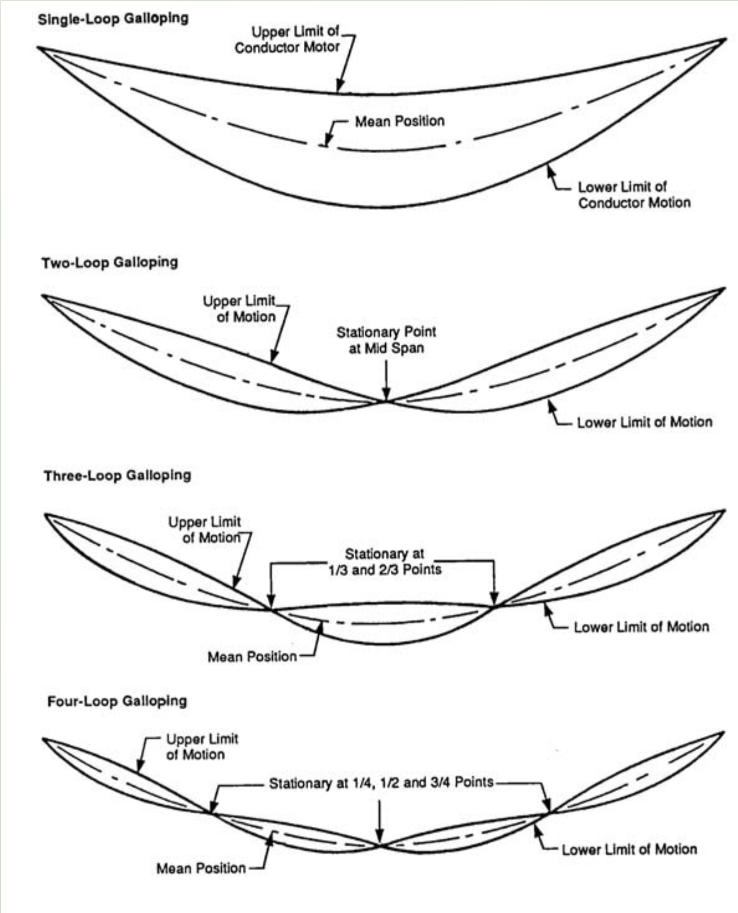


GALLOPING IS:

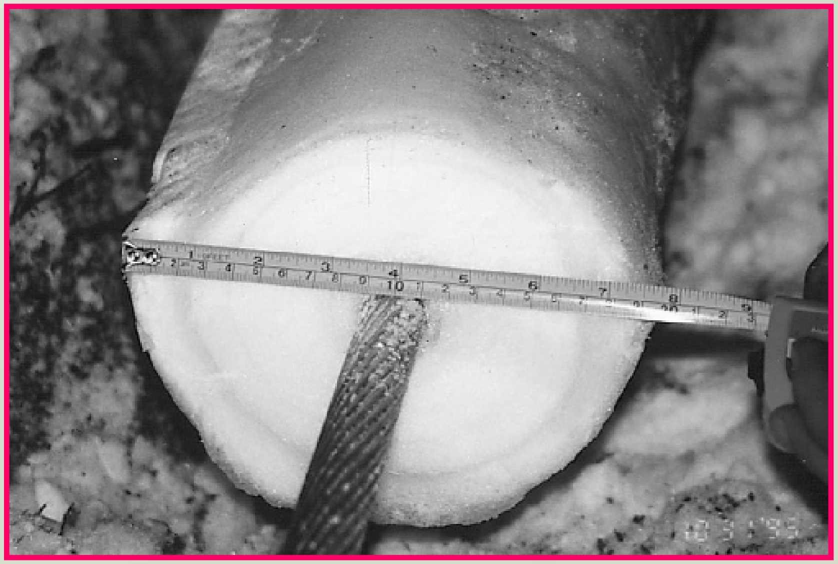
- *A WIND-INDUCED VIBRATION OF BOTH SINGLE AND BUNDLE CONDUCTORS*
- *DIFFERENT FROM AEOLIAN VIBRATION AND WAKE INDUCED OSCILLATION*
- *LOW-FREQUENCY (FROM 0.1 TO 1 HZ)*
- *LARGE VERTICAL AMPLITUDE (FROM ± 0.1 TO < ± 1 TIMES THE SAG)*
- *UP TO 4 TIMES THE SAG ON DISTRIBUTION LINES*
- *A SINGLE OR A FEW LOOPS OF STANDING WAVES PER SPAN*
- *IT APPLIES VERY LARGE DYNAMIC LOADS TO THE STRUCTURES*
- *IT IS A SELF-EXCITED PHENOMENON*

CONDITIONS FOR GALLOPING - ICE

- ***GLAZE ICE, RIME ICE OR WET SNOW ON THE CONDUCTORS (THE ICE LAYER NEED NOT BE THICK)***
- ***GALLOPING CAN OCCUR WITHOUT ICE ON RARE OCCASIONS***
- ***GALLOPING APPEARANCE (NUMBER OF LOOPS, AND PEAK TO PEAK AMPLITUDE)***
- ***CAN BE DIFFERENT ON APPARENTLY SIMILAR CONDUCTORS WITHIN THE SAME SPAN***



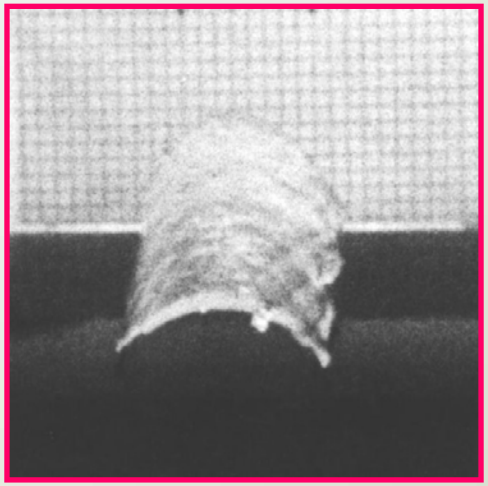
ICE ACCRETION

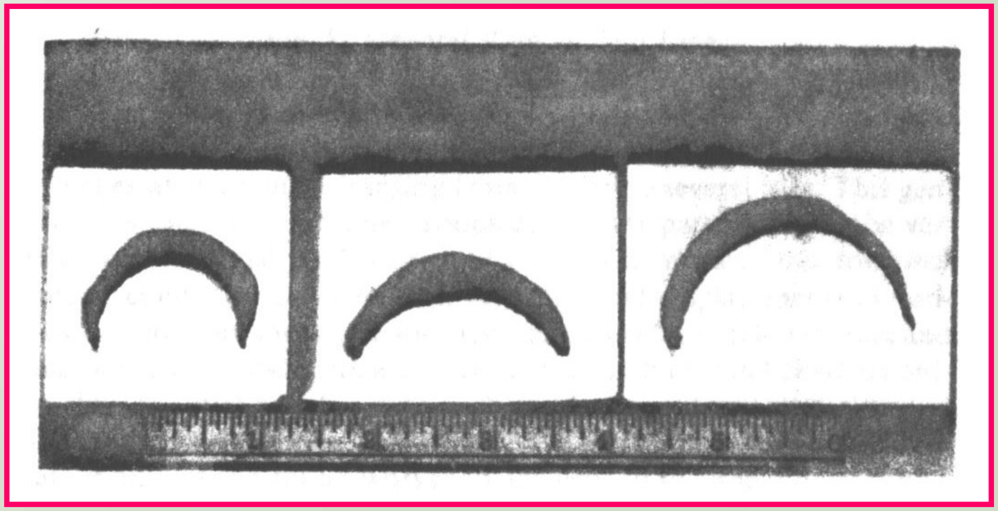


WET SNOW SHAPES

- ***SHOWING NORMAL ROUGH TEXTURE***
- ***ROUNDED PROFILE ON SMALL CONDUCTOR DUE TO CONTINUOUS ROTATION***

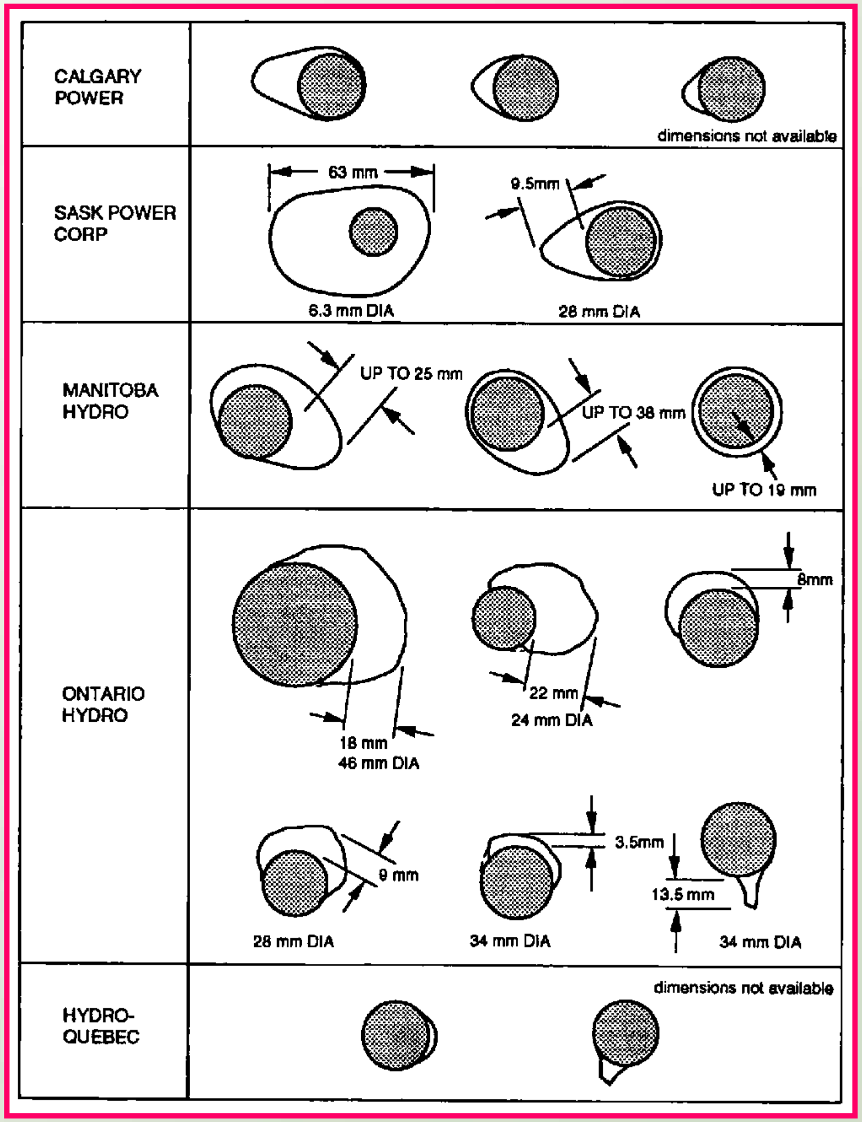
ICE ACCRETION





GLAZE ICE SHAPES FROM SINGLE CONDUCTORS AFTER GALLOPING EVENTS

SHOWING THINNESS OF ICE LAYERS



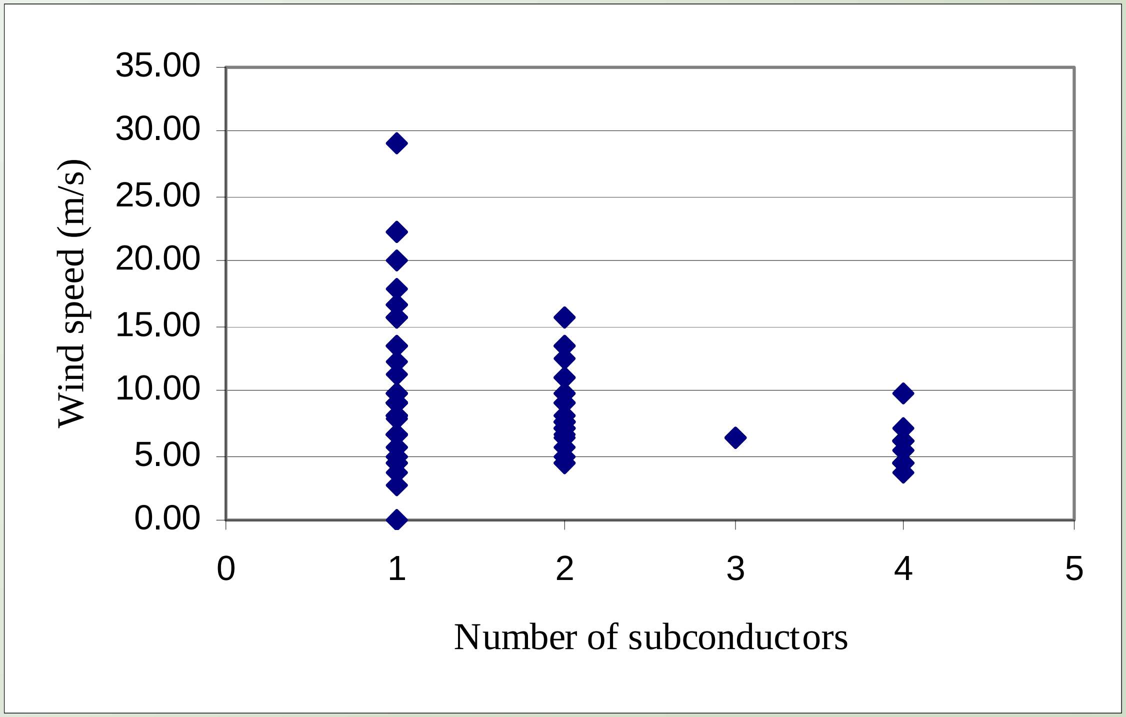
SHAPES OF ICE ACCRETION ON CONDUCTORS DURING GALLOPING

- ***REPORTED IN SURVEY OF CANADIAN ELECTRICAL UTILITIES***
- ***NOTE WIDE VARIATION IN AMOUNT OF ICE AND SEVERAL CASES WITH VERY THIN ICE LAYERS***

CONDITIONS FOR GALLOPING - WIND

- ***MODERATE TO HIGH WIND SPEEDS***
- ***STEADY WINDS***
- ***WIND TRANSVERSE TO THE LINE***
- ***OPEN EXPOSURE OF THE LINE (LOW TURBULENCE)***
- ***RIVER CROSSINGS AND LINES ALONG LAKE FRONTS ARE PARTICULARLY SUSCEPTIBLE***
- ***CAN LAST FOR A FEW HOURS OR SEVERAL DAYS***

WIND SPEEDS FOR GALLOPING



WIND SPEEDS REPORTED DURING GALLOPING FOR SINGLE, TWIN, TRIPLE, AND QUAD BUNDLES

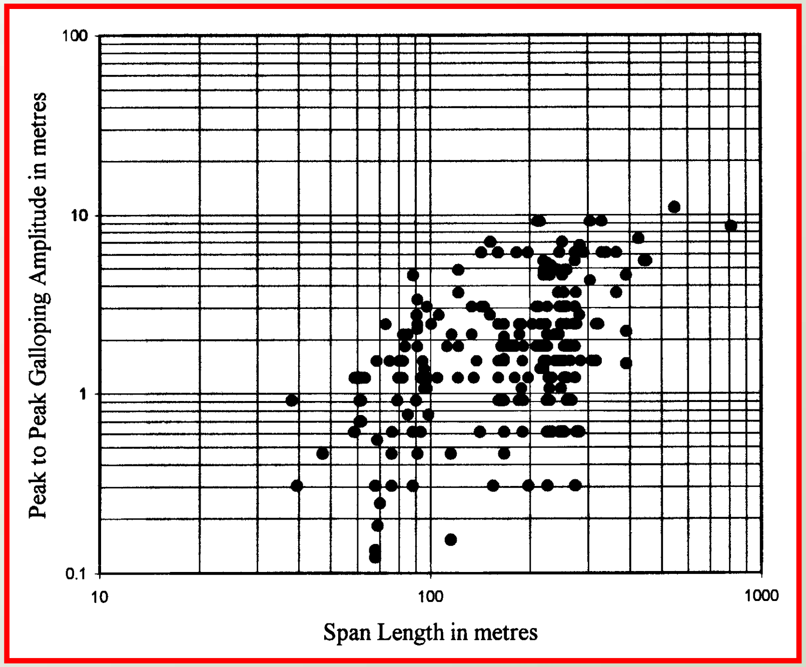
MOST GALLOPING OCCURS AT WINDS SPEEDS ABOVE 5 m/s ON SINGLE AND BUNDLE CONDUCTORS

VIDEO OF GALLOPING - SINGLE CONDUCTOR LINE IN NORWAY

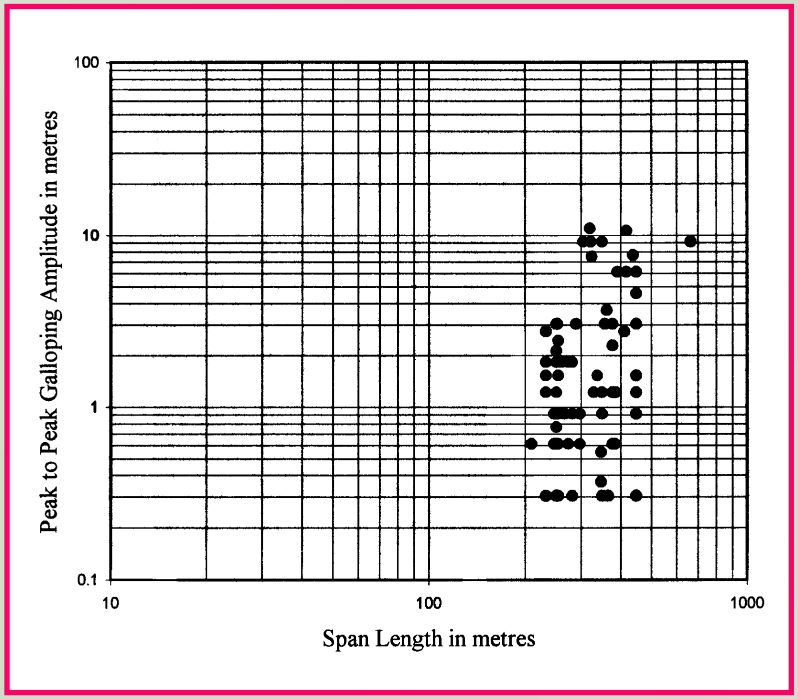
VIDEO OF GALLOPING – TWIN BUNDLE IN ENGLAND

VIDEO OF GALLOPING – QUAD BUNDLE IN JAPAN

GALLOPING AMPLITUDES



PEAK TO PEAK GALLOPING AMPLITUDES VERSUS SPAN LENGTH OBSERVED IN THE FIELD

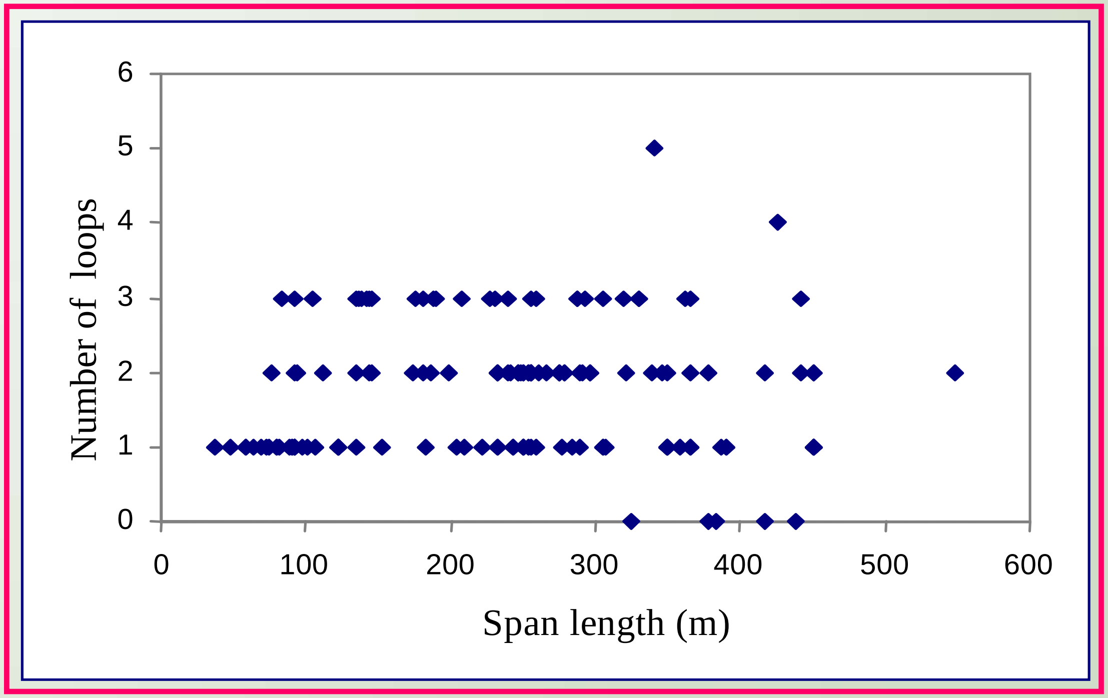


ABOVE: SINGLE CONDUCTORS

RIGHT: BUNDLE CONDUCTORS

(FROM FIELD STUDIES IN USA AND CANADA)

NUMBER OF GALLOPING LOOPS



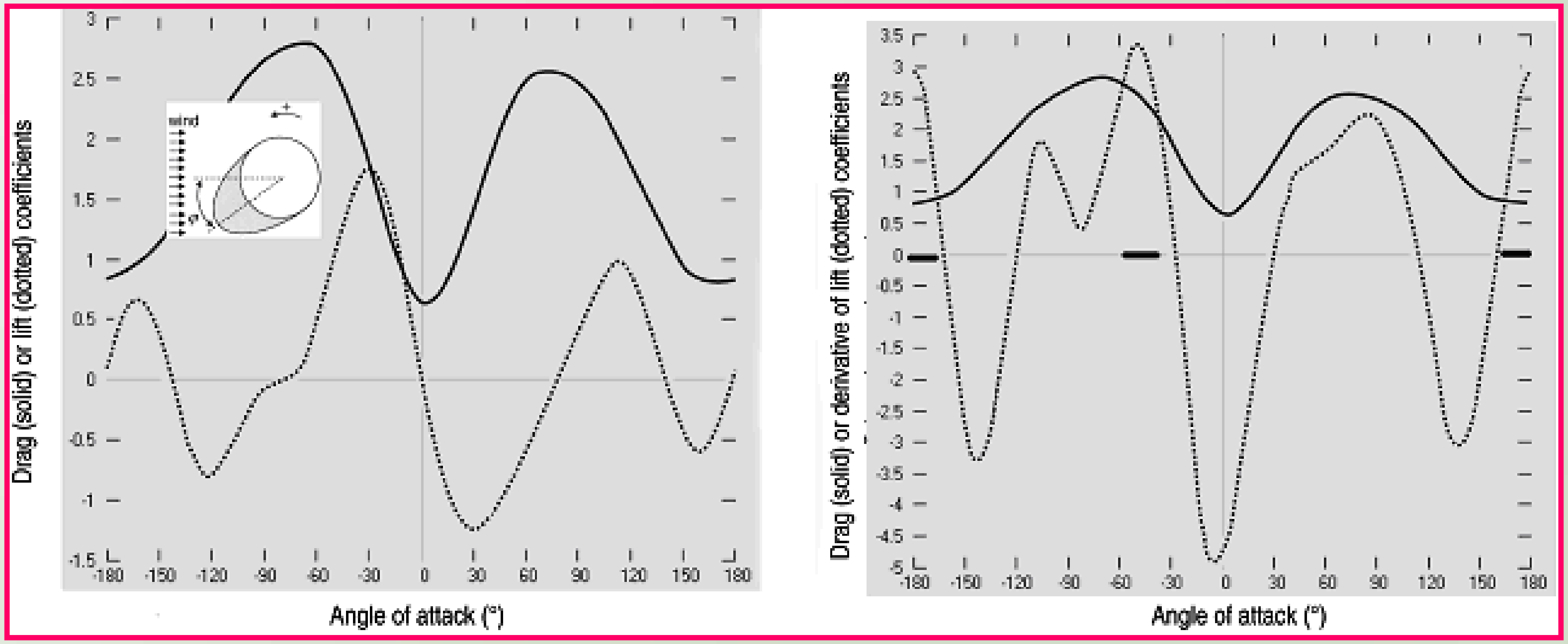
NUMBER OF LOOPS OBSERVED DURING GALLOPING VERSUS SPAN LENGTH

- ***BASED ON ANALYSIS OF FIELD DATA FROM ALL GALLOPING OBSERVATIONS***
- ***DATA FROM SINGLE AND BUNDLE CONDUCTOR SITES***
- ***SHOWS THAT SINGLE LOOP GALLOPING CAN OCCUR ON LONG SPANS***
- ***GALLOPING CAN INCLUDE TRAVELING WAVES***

DEN HARTOG MECHANISM

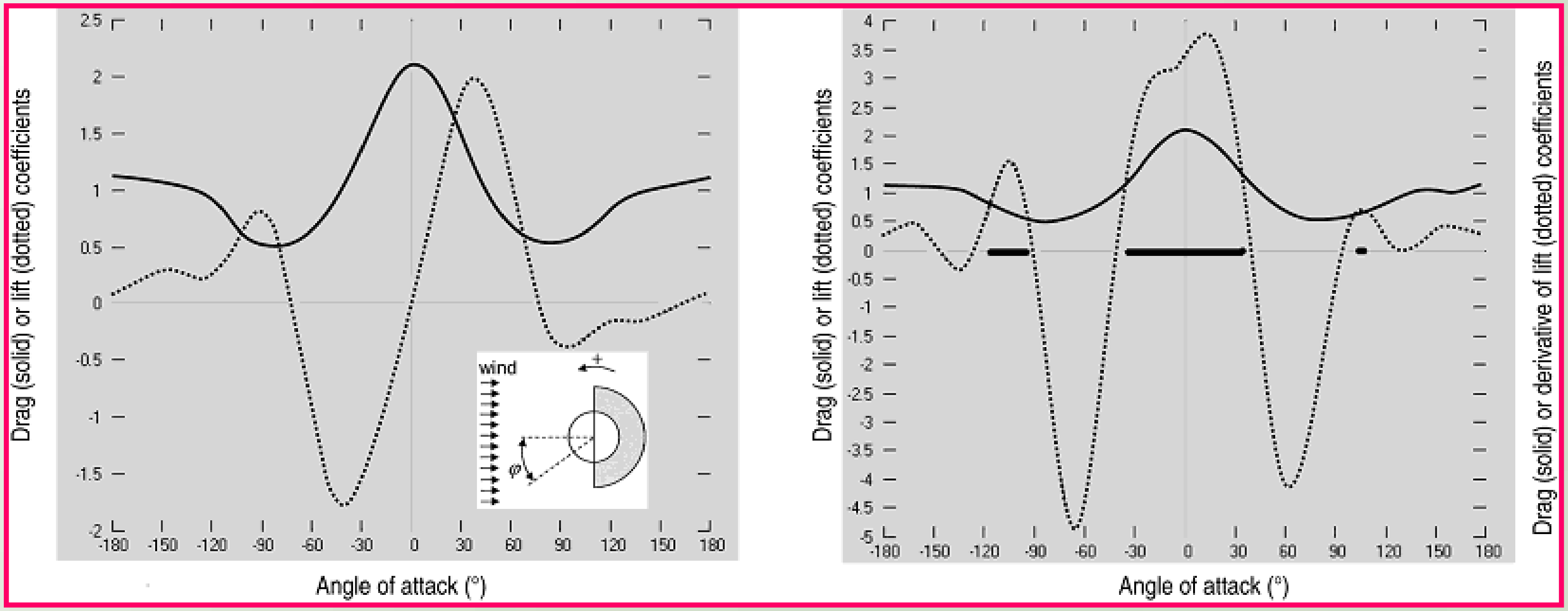
- *ONLY AERODYNAMIC FORCES ARE IMPORTANT*
- *PREDICTS GALLOPING WHEN SLOPE OF THE LIFT COEFFICIENT CURVE (DOTTED) IS GREATER THAN THE DRAG COEFFICIENT (SOLID)*

$$C_D - C_{L\alpha} < 0$$



- *TORSION IS EITHER NEGLIGIBLE OR FORCED BY VERTICAL MOVEMENT*
- *TORSIONAL FREQUENCY AND DAMPING NOT IMPORTANT*
- *PROBABLY RARE, EXCEPT FOR REVERSE WIND*

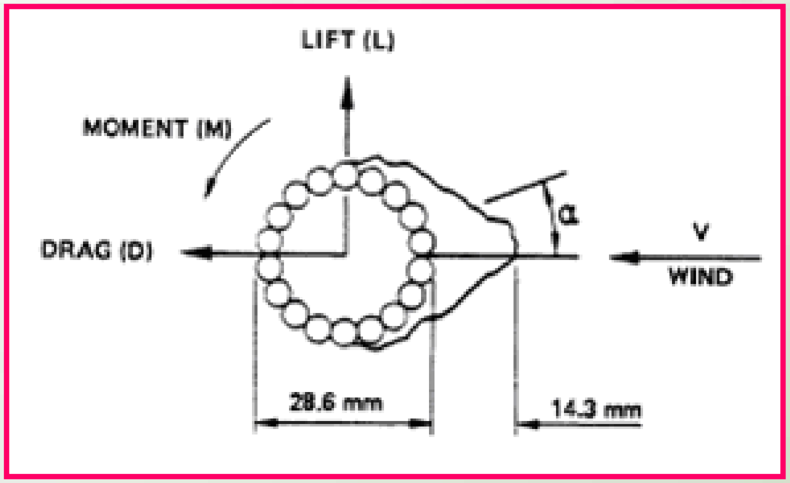
AERODYNAMIC PROPERTIES OF “D” SECTION



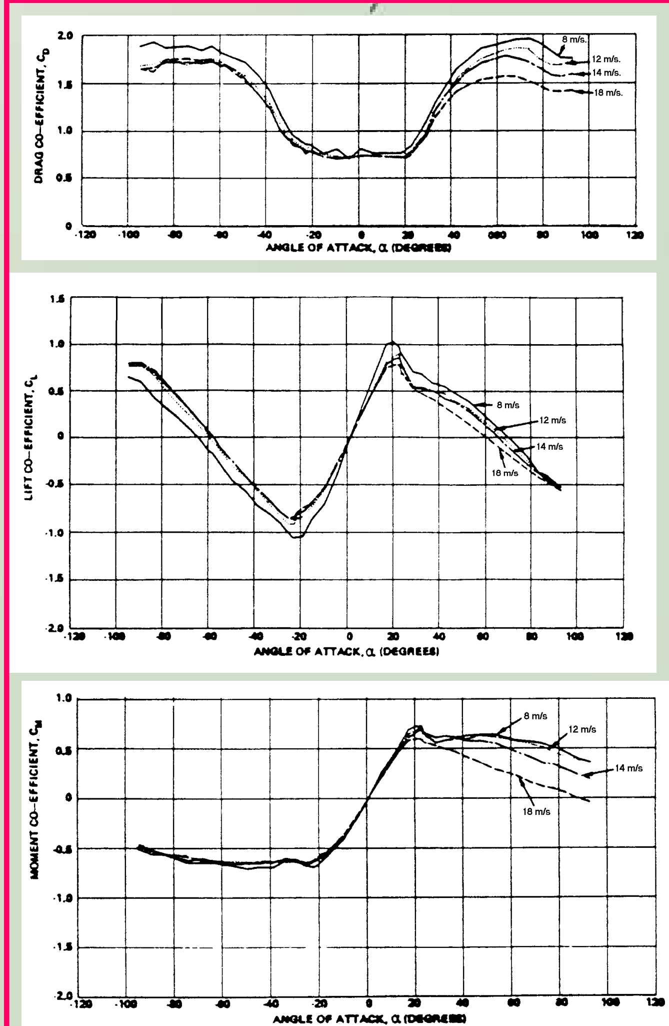
LEFT: LIFT AND DRAG COEFFICIENTS VERSUS ANGLE OF ATTACK, INSET SHOWS “D” PROFILE USED ON HYDRO QUÉBEC TEST LINE

RIGHT: RATE OF CHANGE OF LIFT AND DRAG COEFFICIENTS WITH DEN HARTOG INSTABILITY REGIONS

AERODYNAMICS OF ICE SHAPES

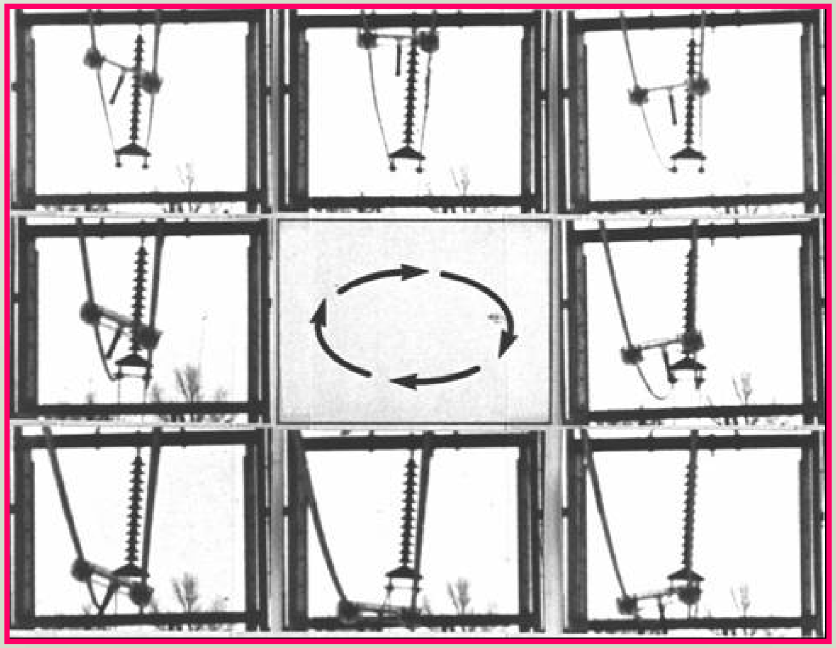


- *WET SNOW SHAPE FROM TEST FRAME IN ENGLAND*
- *AERODYNAMIC DRAG, LIFT AND MOMENT VERSUS ANGLE OF ATTACK DRIVE THE INSTABILITY (REVERSED SIGN OF ANGLE OF ATTACK)*
- *NEGATIVE SLOPE OF THE LIFT CURVE INDICATES SELF EXCITED OSCILLATIONS OF THE PROFILE*
- *ROTATION OF THE SECTION INCREASES THE RANGE OF UNSTABLE POSITIONS OF THE ICE*



FLUTTER MECHANISM

- *COUPLING BETWEEN VERTICAL AND TORSIONAL MOVEMENT IS CENTRAL TO THE MECHANISM*
- *TORSION IS ESSENTIAL FOR ENERGY TRANSFER TO VERTICAL MOVEMENT*
- *STRUCTURAL DATA AND AERODYNAMICS IMPORTANT*
- *RATIO VERTICAL TO TORSIONAL FREQUENCY IMPORTANT*
- *CONTROL OF TORSION BY DAMPING OR DETUNING IS ESSENTIAL FOR CONTROL*
- *PROBABLY THE MOST COMMON MECHANISM, PARTICULARLY ON BUNDLE CONDUCTOR LINES*



$$(C_D - C_{L\alpha})\frac{\omega y_{\max}}{V} < C_{L\alpha}.\vartheta_{\max}.\sin\phi$$

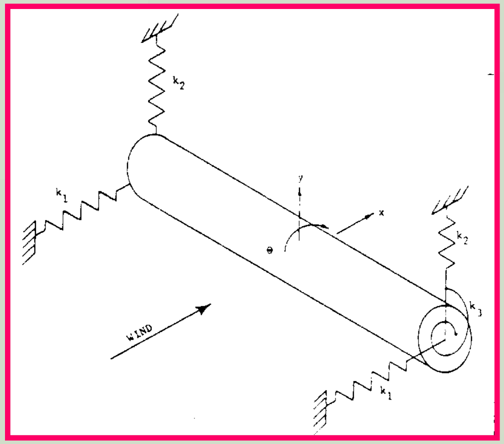
PREDICTION OF GALLOPING MOTIONS

$$
\underbrace{\begin{bmatrix} m & & me_y \\ & m & me_x \\ me_y & me_x & I \end{bmatrix}}_{\text{INERTIA}} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{Bmatrix} + \underbrace{\begin{bmatrix} k_{xx} & k_{xy} & \\ k_{yx} & k_{yy} & \\ & & K_{\theta\theta} \end{bmatrix}}_{\text{SPRINGS}} \begin{Bmatrix} x \\ y \\ \theta \end{Bmatrix}
$$

$$
+ \underbrace{\begin{bmatrix} R_x & & \\ & R_y & \\ & & R_\theta \end{bmatrix}}_{\text{MECHANICAL DAMPING}} \begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{Bmatrix} - \underbrace{\begin{bmatrix} 0 & & \\ & 0 & \\ & & We_y \end{bmatrix}}_{\text{ICE WEIGHT}} \begin{Bmatrix} x \\ y \\ \theta \end{Bmatrix}
$$

$$
- \frac{\rho d V^2}{2} \underbrace{\begin{bmatrix} 0 & & C_{D\alpha} \\ & 0 & C_{L\alpha} \\ & & dC_{M\alpha} \end{bmatrix}}_{\text{AERO-ELASTIC}} \begin{Bmatrix} x \\ y \\ \theta \end{Bmatrix} + \frac{\rho d V}{2} \underbrace{\begin{bmatrix} VC_{DV}+2C_D & C_{D\alpha}-C_L & \\ VC_{LV}+2C_L & C_{L\alpha}+C_D & \\ d(VC_{MV}+2C_M) & dC_{M\alpha} & dVC_{M\dot{\alpha}} \end{bmatrix}}_{\text{AERODYNAMIC DAMPING}} \begin{Bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{Bmatrix}
$$

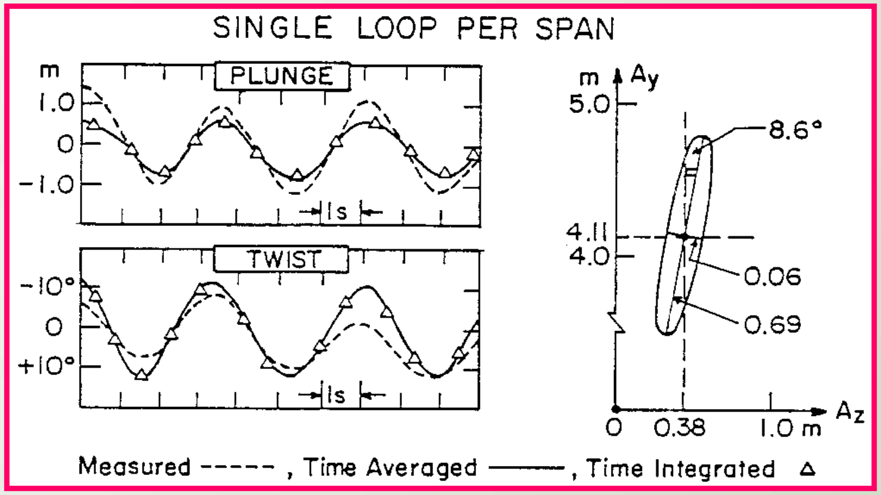
$$
= \{ 0 \}
$$

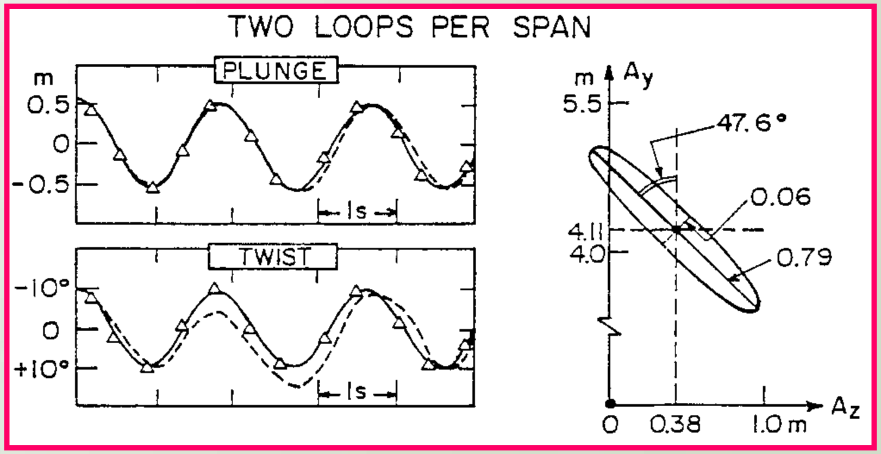


LUMPED MASS MODEL OF GALLOPING CONDUCTOR

- ***EQUATIONS REPRESENTING LINEARIZED GALLOPING INCLUDING HORIZONTAL, VERTICAL AND TORSIONAL MOTIONS, BUT NOT LONGITUDINAL MOTIONS***
- ***THIS PRESENTATION IDENTIFIES THE INERTIA EFFECTS, SPRING FORCES, DAMPING, AND WEIGHT AND AERODYNAMIC FACTORS (RAWLINS 1979)***

PREDICTION OF GALLOPING MOTIONS





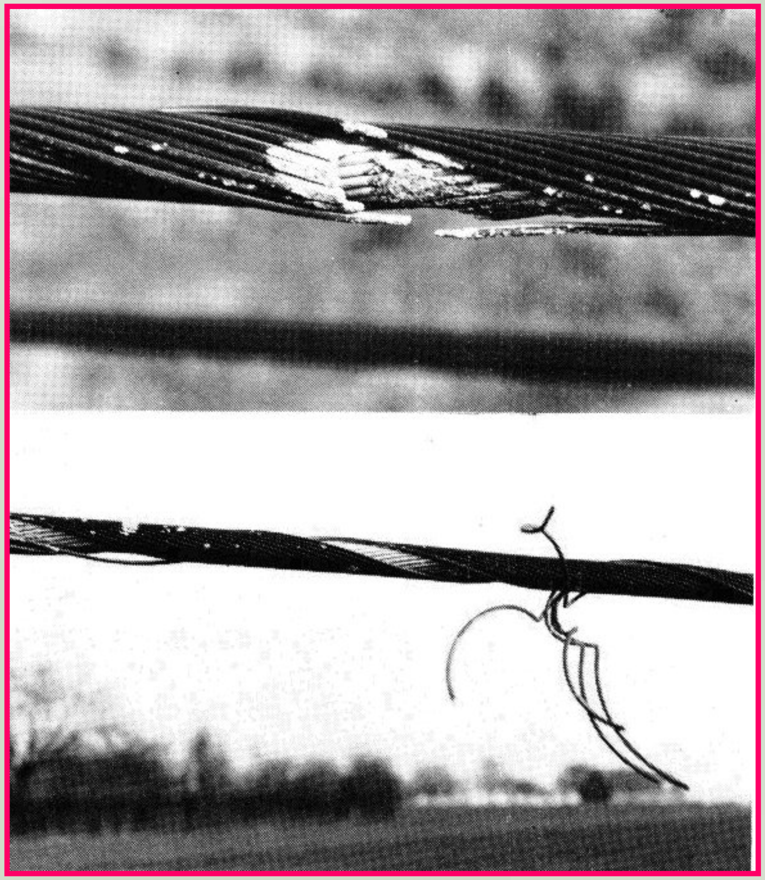
- *COMPARISONS OF FINITE ELEMENT PREDICTION AND MEASURED SINGLE AND TWO -LOOP GALLOPING MOTIONS OF A SECTION OF ICED CONDUCTOR MODEL IN A WIND TUNNEL*
- *ICE WAS REPRESENTED BY A SMOOTH ELLIPTICAL PLASTIC FOIL ON THE WINDWARD SIDE OF THE CONDUCTOR*
- *SIMULATION OF ACTUAL LINES REQUIRES MODELING OF SEVERAL SPANS TOGETHER AND DATA ON THE ICE OR WET SNOW SHAPE AND DENSITY*

DAMAGE DUE TO GALLOPING

MANY GALLOPING EVENTS CAUSE NO DAMAGE, BUT SEVERE AND PROLONGED GALLOPING APPLIES MANY REPETITIONS OF HIGH LOADS WHICH MUST BE COMPARED TO THE FATIGUE STRENGTH OF THE STRUCTURES AND COMPONENTS

EFFECTS OF MODEST GALLOPING:

- *FLASHOVERS BETWEEN VERTICALLY ALIGNED PHASES*
- *CIRCUIT OUTAGES AND*
- *BURNS OF CONDUCTORS*
- *DAMAGE TO BREAKERS IF THE CIRCUIT IS NOT ISOLATED*

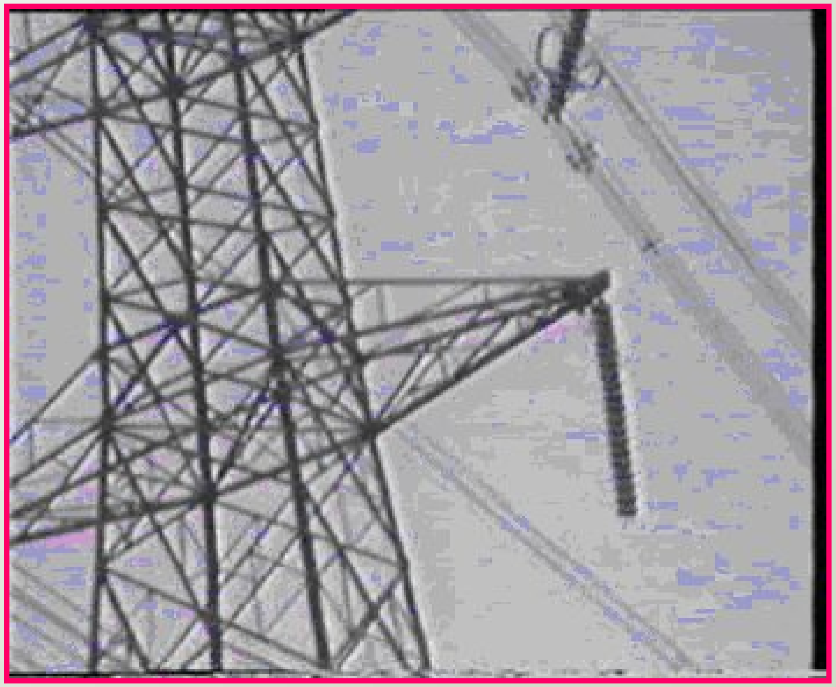


CONDUCTOR BURNS DUE TO GALLOPING

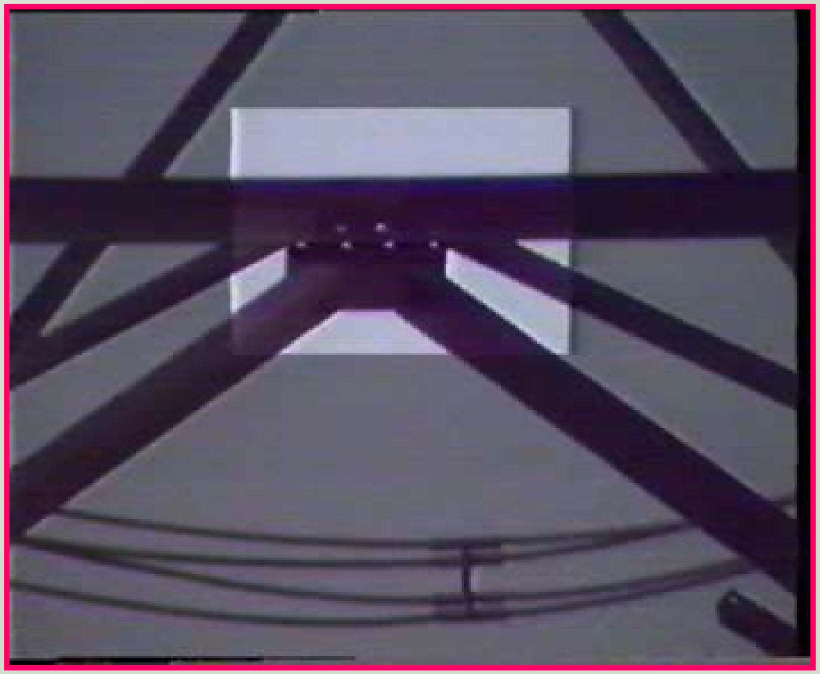
DAMAGE DUE TO GALLOPING

EFFECTS OF MODEST GALLOPING:

- *LOOSENED BOLTS*
- *SEPARATED INSULATOR STRINGS*



INSULATOR STRING SEPARATED DURING GALLOPING



TOWER GUSSET PLATE WITH ALL BOLTS FATIGUED DUE TO DYNAMIC LOADS ON A STRAIN TOWER DURING GALLOPING

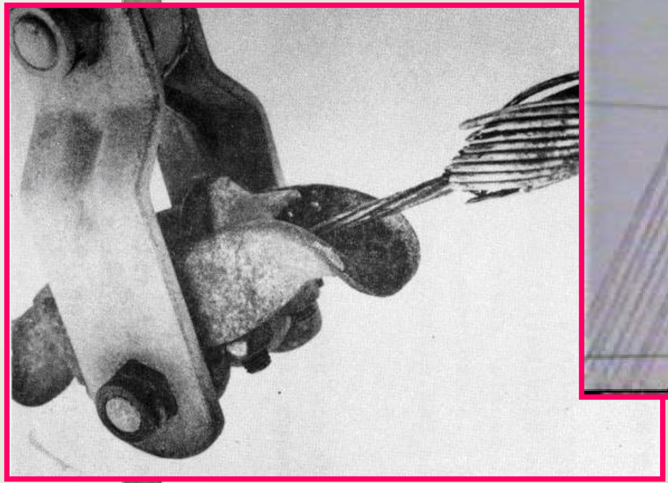
DAMAGE DUE TO GALLOPING

EFFECTS OF MODEST GALLOPING:

- ***BROKEN HARDWARE***
- ***FATIGUED CONDUCTOR STRANDS***

SPACER DAMPER BROKEN DUE TO GALLOPING

JUMPER LOOPS OF QUAD BUNDLE BROKEN DUE TO GALLOPING



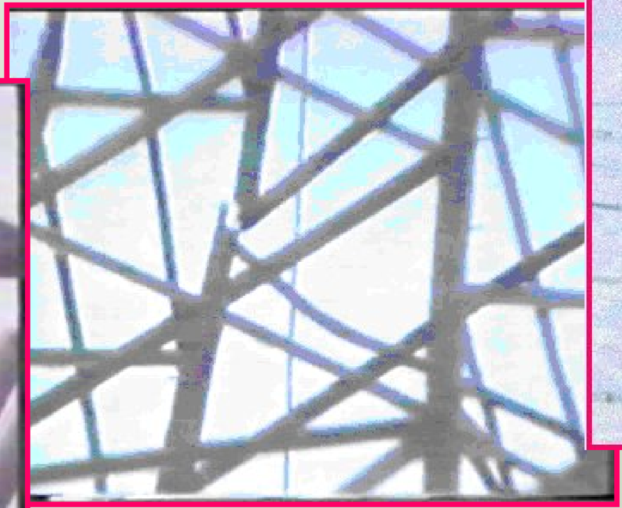
CONDUCTOR FATIGUE DAMAGE DUE TO GALLOPING

DAMAGE DUE TO GALLOPING

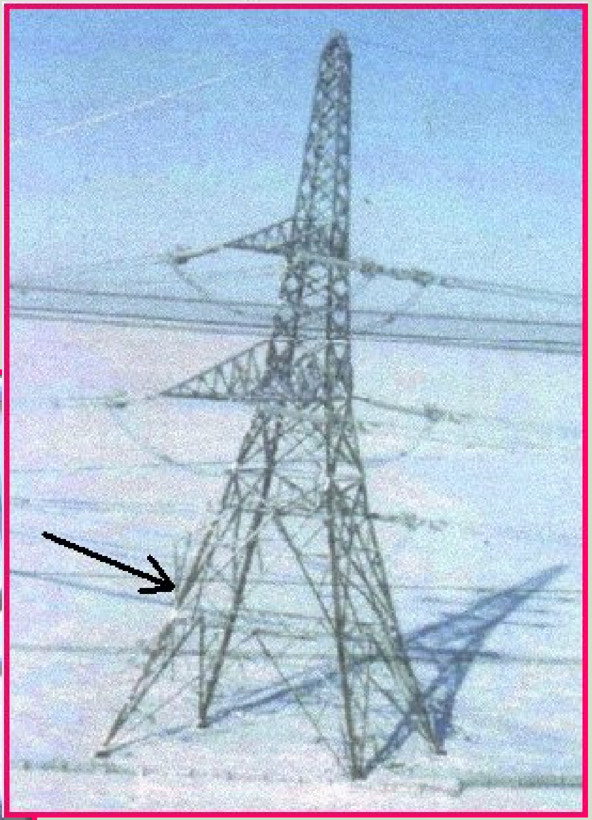
EFFECTS OF SEVERE AND PROLONGED GALLOPING:

- ***FRACTURED TOWER MEMBERS***
- ***COLLAPSED TOWER ARMS***
- ***CASCADES OF LINE SECTIONS***

TOWER ARM BRACING MEMBERS BROKEN DUE TO GALLOPING



TOWER MAIN LEG BROKEN DURING GALLOPING



TOWER WITH LOWER ARM FAILED DUE TO GALLOPING

DYNAMIC LOADS DURING GALLOPING

MEASURED VERTICAL LOADS

SOURCE	CONDUCTOR	SPAN LENGTHS	STATIC LOAD kg	DYNAMIC LOAD kg	RATIO
ANJO et al. 1974	4 x 410 mm^2	312 m, 319 m	2100	3500	1.7
	4 x 950 mm^2	312 m, 319 m	4070	2500	0.6
KRISHNASAMY 1984	34 mm DIAM	459 m	1046	1990	1.9
	28 mm DIAM	418 m	677	810	1.2
	41 mm DIAM	216 m	626	1250	2.0
BROKENSHIRE 1979	2 x 30.4 mm DIAM	312 m, 308 m	1387	375	0.2
	2 x 30.4 mm DIAM	291 m, 242 m	1431	466	0.3
	2 x 30.4 mm DIAM	259 m, 251 m	1067	245	0.2
	2 x 36.2 mm DIAM	232 m, 256 m	1226	1364	1.1

DYNAMIC LOADS DURING GALLOPING

MEASURED HORIZONTAL LOADS

SOURCE	CONDUCTOR	SPAN LENGTHS	STATIC LOAD kg	DYNAMIC LOAD kg	RATIO
ANJO et al. 1974	4 x 410 mm²	312 m, 319 m	6150	7400	1.2
	4 x 950 mm²	312 m, 319 m	9300	7800	0.8
ESCARMELLE et al. 1997	2 X 620 mm ²	308 m	3600	4000	1.1
	2 X 620 mm ²	308 m	3600	7500	2.1
MORISHITA et al. 1984	4 X 410 mm ²	363 m, 247 m	2400	3120	1.3
	8 X 810 mm ²	230 m, 190 m	3000	3180	1.1
	6 X 410 mm ²	363 m, 247 m	2400	1920	0.8
	8 X 410 mm ²	353 m, 230 m, 350 m	2300	1470	0.6
	10 X 810 mm ²	230 m, 190 m	3000	1200	0.4
ELIASON 2002	28.1 mm DIAM	80 m	840	1870	2.2
	28.1 mm DIAM	80 m	800	2150	2.7
	28.1 mm DIAM	80 m	780	2160	2.8
	28.1 mm DIAM	80 m	800	1040	1.3

CONTROL OF GALLOPING

ICE MELTING

- *USED WHERE THE POWER TO CUSTOMERS CAN BE CUT OFF AND TAPS ARE PROVIDED TO CONNECT HIGHER THAN NORMAL CURRENT THROUGH THE LINES*

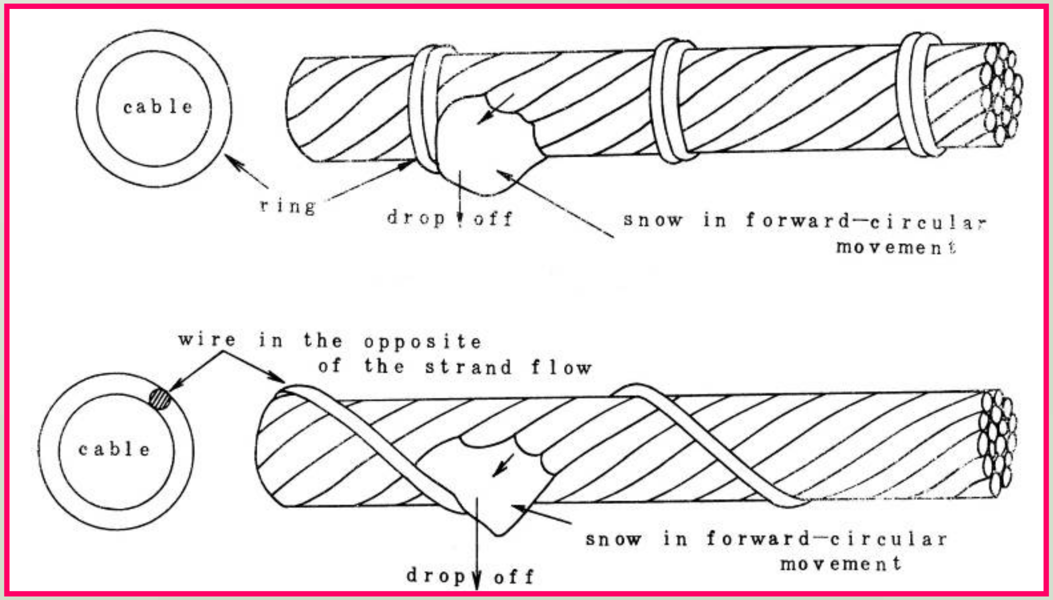
ICE REMOVAL

- *MECHANICAL ICE REMOVAL USING A ROLLER*

ICE PREVENTION

- *NO SUCCESSFUL ICE-PHOBIC COATING HAS BEEN DEVELOPED*

- *WET SNOW ACCRETIONS ARE BEING REDUCED THROUGH RINGS AND SPIRALLY WRAPPED WIRES IN JAPAN*

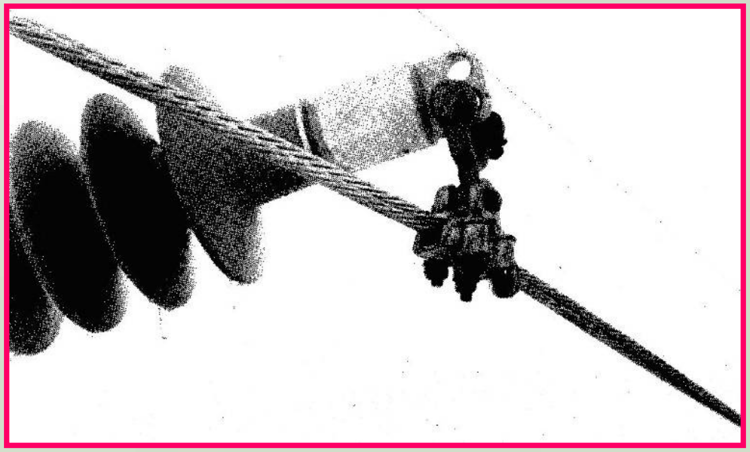


RINGS AND SPIRALS TO REMOVE WET SNOW

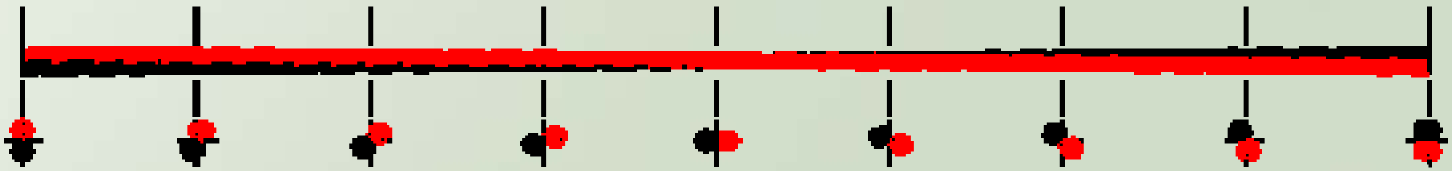
CONTROL OF GALLOPING

MODIFIED CONDUCTOR PROFILES

- *AERODYNAMICALLY MORE STABLE PROFILES SUCH AS THE TWISTED PAIR (T2 OR VR) AND ADDED PLASTIC SPIRALS SHOW REDUCTIONS IN GALLOPING OCCURRENCES AND SEVERITY*



TWISTED PAIR CONDUCTOR

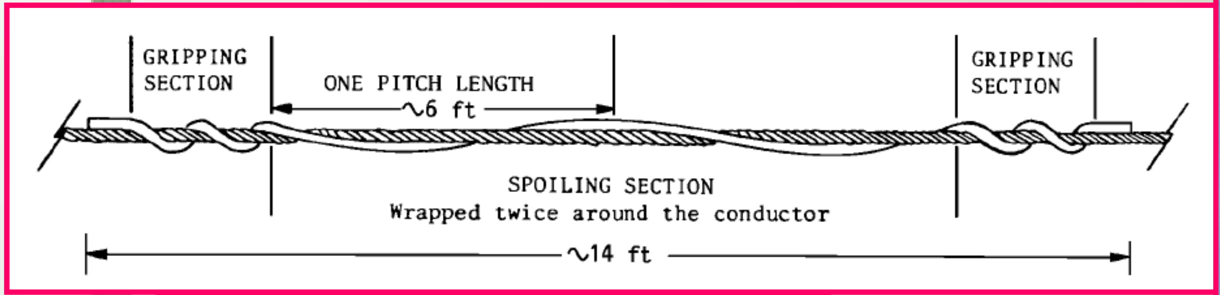


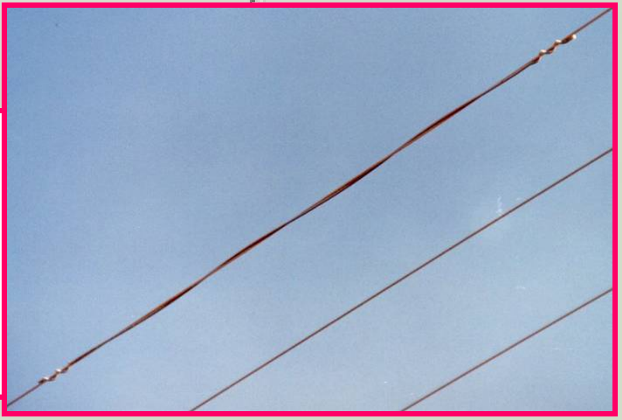
THE VARYING PROFILE ACROSS THE SPAN CREATES ALTERNATELY UPWARD AND DOWNWARD WIND FORCES WITH A NET REDUCTION IN TOTAL LIFT FORCE, UNLESS THE ICE LAYER THICKNESS OBSCURES THE SHAPE EFFECT

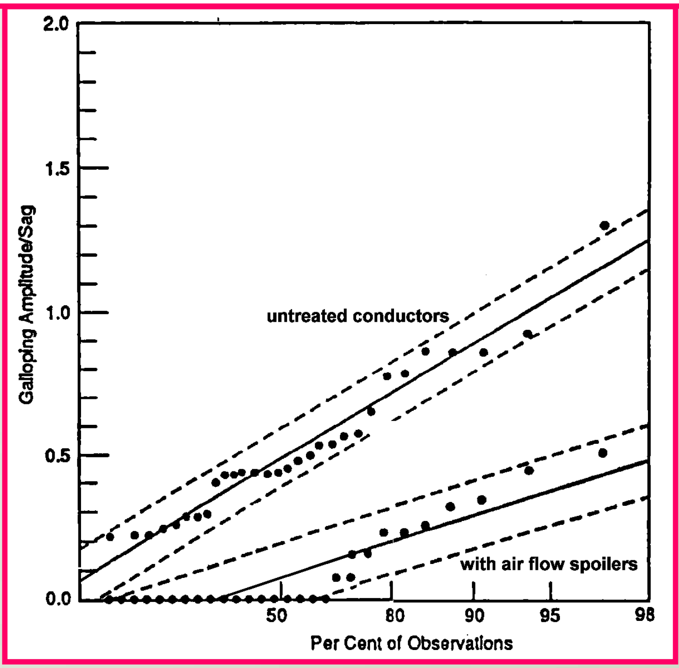
CONTROL OF GALLOPING

MODIFIED CONDUCTOR PROFILES

AIR FLOW SPOILERS FOR LOW VOLTAGE LINES



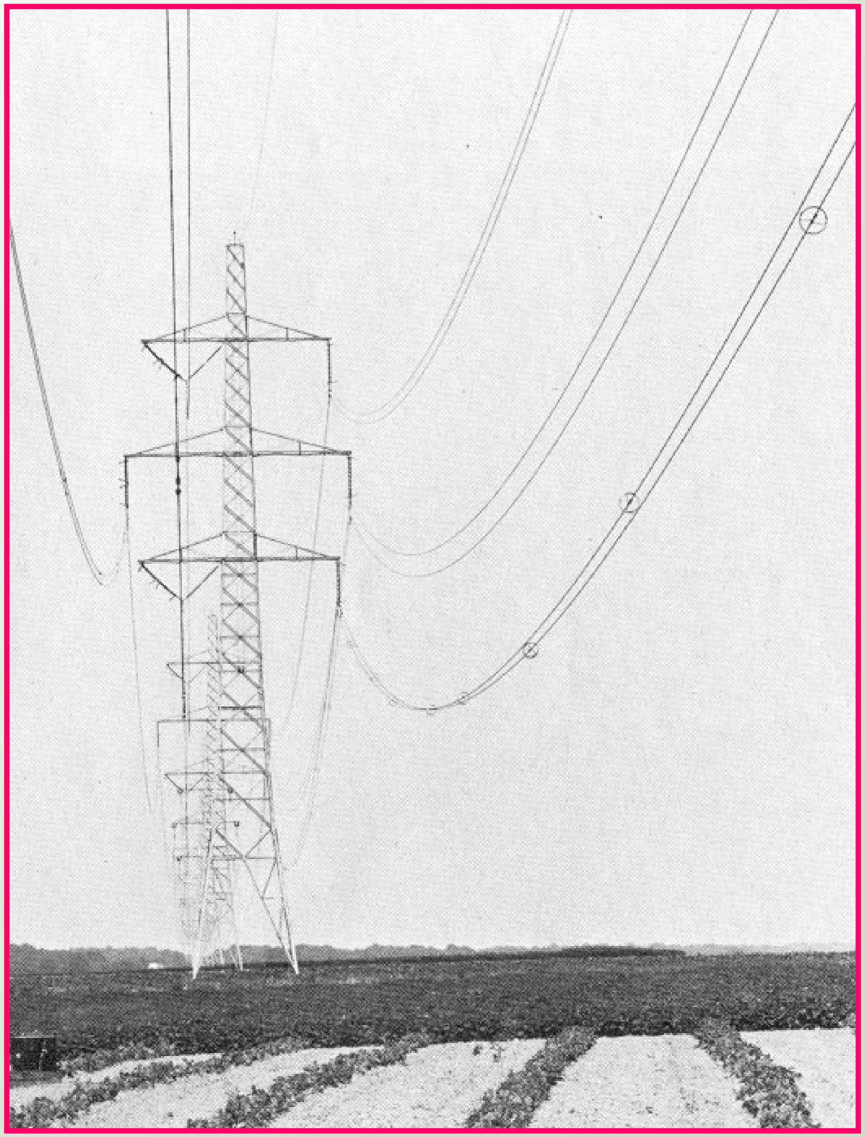




DATA FROM 31 FIELD OBSERVATIONS ON DISTRIBUTION LINES

- ***COMPARISON OF GALLOPING AMPLITUDES ON UNTREATED CONDUCTORS AND CONDUCTORS WITH AIR FLOW SPOILERS***
- ***AMPLITUDES SHOWN DIVIDED BY SAG TO NORMALIZE DATA FROM DIFFERENT SPAN LENGTHS***
- ***MAXIMUM GALLOPING AMPLITUDE REDUCED TO ABOUT 1/4 BY AIR FLOW SPOILERS***
- ***FORCES APPROX. EQUAL TO AMPLITUDE SQUARED***

CONTROL OF GALLOPING

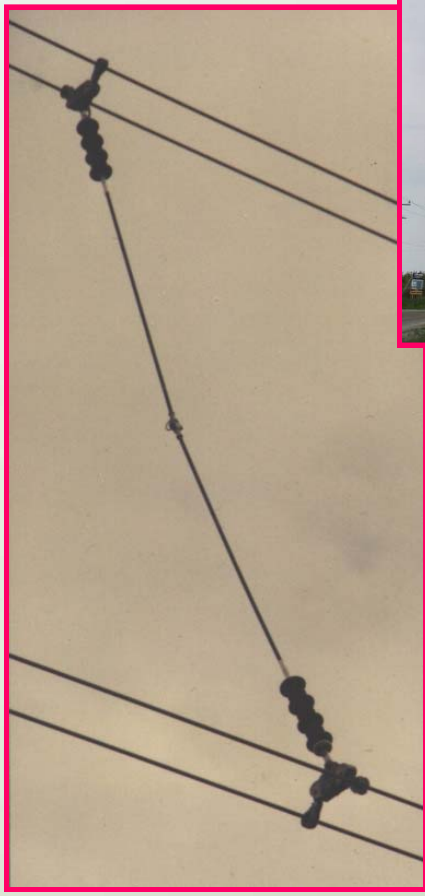


BUNDLE MODIFICATION

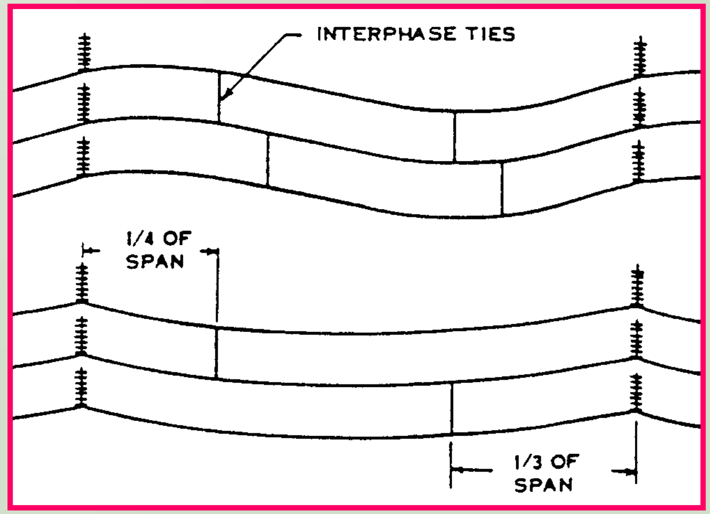
- *ROTATE BUNDLE TO VERTICAL*
- *SEPARATE SUBCONDUCTORS WITH HOOP SPACERS*
- *REDUCES TORSIONAL STIFFNESS OF THE SPAN AND ALLOWS WET SNOW TO FALL OFF AS THE CONDUCTORS ROLL UNDER THE ADDED WEIGHT*
- *NEED TO DISTINGUISH BETWEEN GLAZE ICE AND WET SNOW*

CONTROL OF GALLOPING

RIGID AND FLEXIBLE INTERPHASE SPACERS



- *POLYMERIC MATERIALS COMMONLY USED*
- *CORONA RINGS AT HIGH VOLTAGES*

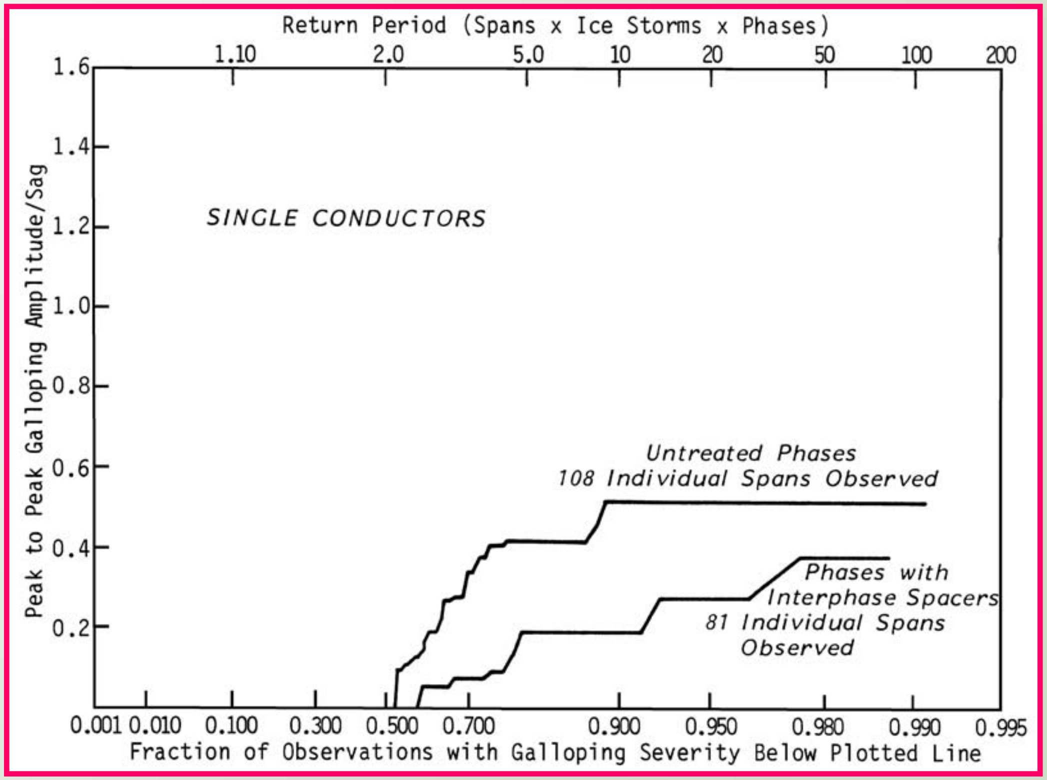


IN SPAN LOCATIONS

- *NEED TO AVOID MID-POINT*
- *TWO INTERPHASE SPACERS PER SPAN ON SHORT SPANS*
- *FOUR INTERPHASE SPACERS PER SPAN ON LONG SPANS*
- *POSSIBLE CLASHING WHEN TWO INTERPHASE SPACERS ARE USED*

CONTROL OF GALLOPING

INTERPHASE SPACERS



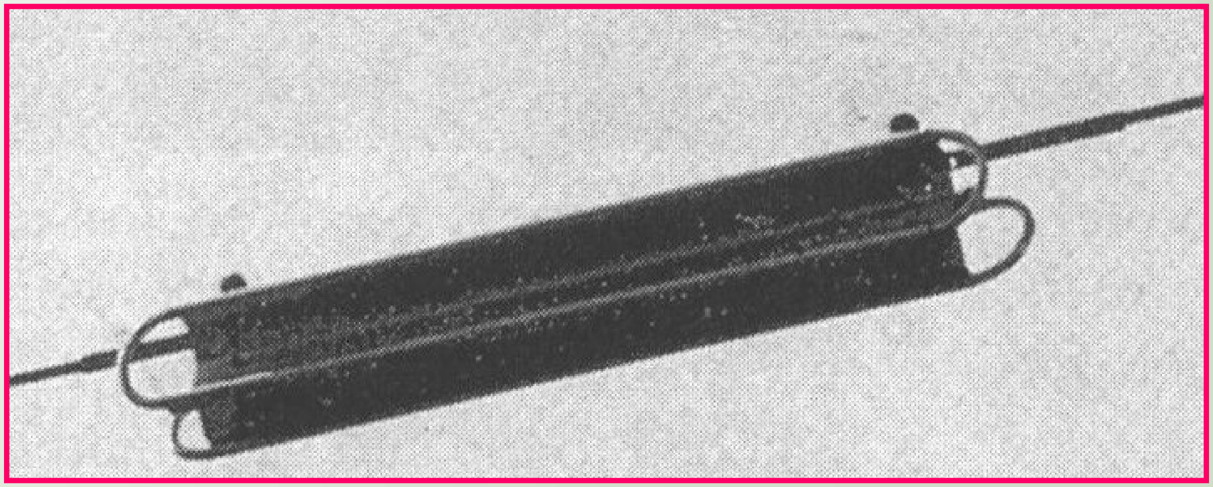
DATA FROM 10 FIELD OBSERVATIONS

- ***COMPARISON OF GALLOPING AMPLITUDES ON UNTREATED CONDUCTORS AND CONDUCTORS WITH INTERPHASE SPACERS***
- ***AMPLITUDES SHOWN DIVIDED BY SAG TO NORMALIZE DATA FROM DIFFERENT SPAN LENGTHS***
- ***MAXIMUM GALLOPING AMPLITUDE REDUCED TO ~1/2***

VIDEO OF TWIN BUNDLE TEST LINE WITH "D" SECTION AIRFOILS AND INTERPHASE SPACERS (IREQ)

CONTROL OF GALLOPING

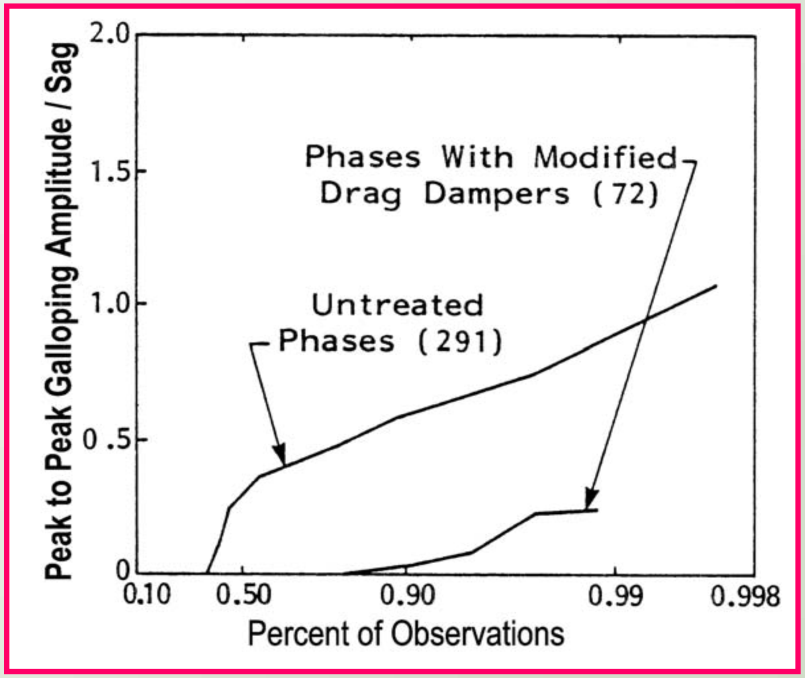
AERODYNAMIC DRAG DAMPER



- *GENERATES TORSIONAL MOTION TO SMOOTH THE ICE PROFILE*
- *VANES INCREASE BOTH AERODYNAMIC DRAG AND THE AERODYNAMIC DAMPING OF THE CONDUCTOR FOR GALLOPING CONTROL.*
- *MODIFIED DESIGN TESTED HAS A SLIGHT CHANGE OF ANGLE OF THE TWO CONCAVE SURFACES TO OPTIMIZE THE AERODYNAMIC CHARACTERISTICS*
- *MODIFIED VERSION WAS INSTALLED WITH BOTH HEAVY (45 kg, 100 lb) AND LIGHT (14 kg, 30 lb) DESIGNS IN EACH SPAN*

CONTROL OF GALLOPING

AERODYNAMIC DRAG DAMPER



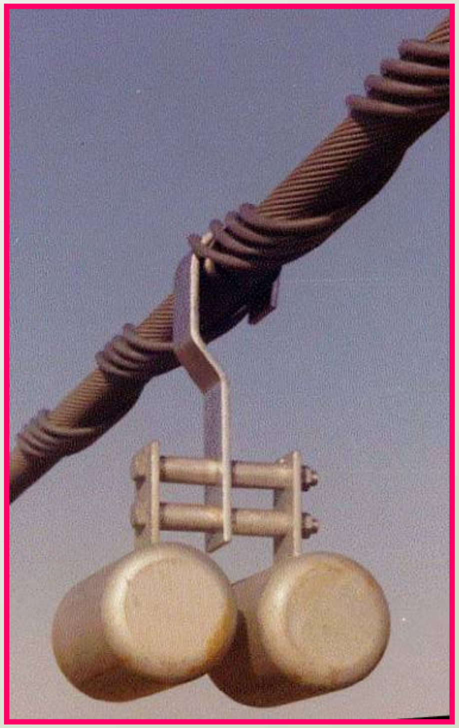
DATA FROM 8 FIELD OBSERVATIONS ON SINGLE CONDUCTORS

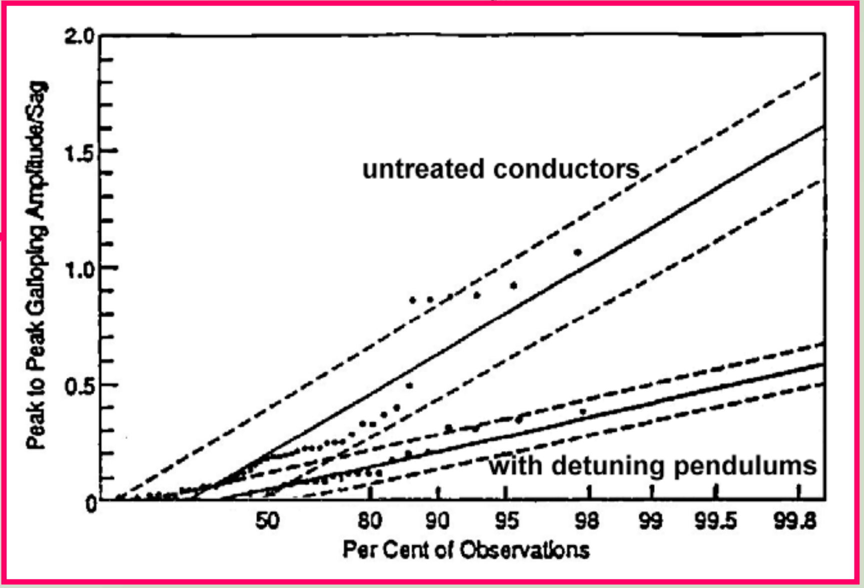
- ***COMPARISON OF GALLOPING AMPLITUDES ON UNTREATED CONDUCTORS AND CONDUCTORS WITH MODIFIED DRAG DAMPERS***
- ***AMPLITUDES SHOWN DIVIDED BY SAG TO NORMALIZE DATA FROM DIFFERENT SPAN LENGTHS***
- ***MAXIMUM GALLOPING AMPLITUDE REDUCED TO ~1/3***

CONTROL OF GALLOPING

TORSIONAL DEVICES

- *DETUNING PENDULUM FOR SINGLE CONDUCTORS*
- *THREE OR FOUR PER SPAN*
- *ARM LENGTH CONTROLS FREQUENCY*
- *WEIGHT CONTROLS AMOUNT OF ICE*





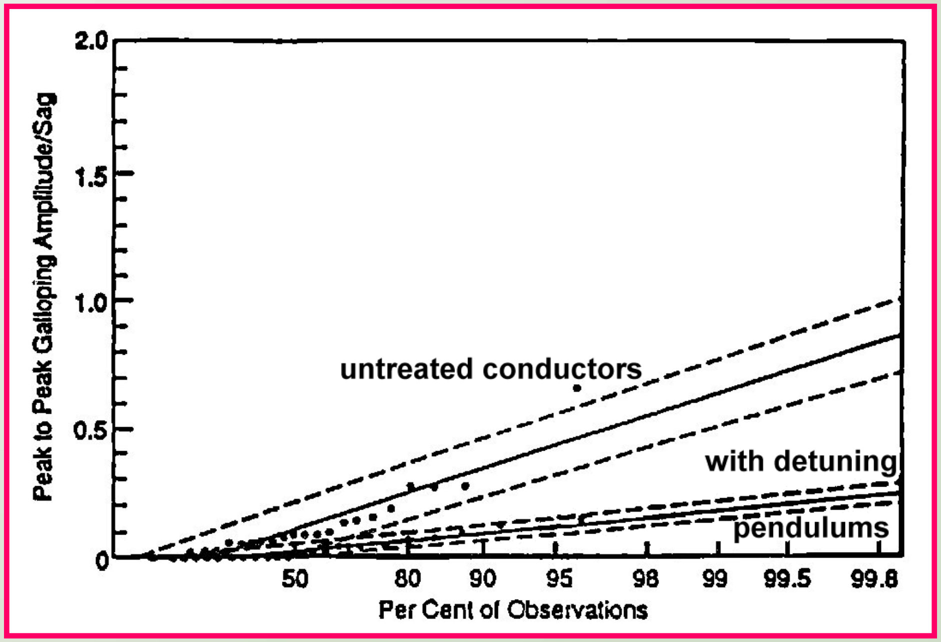
DATA FROM 43 FIELD OBSERVATIONS ON SINGLE CONDUCTORS (25 – 50 mm DIAM, 120 – 480 m SPANS)

- *COMPARISON OF GALLOPING AMPLITUDES ON UNTREATED CONDUCTORS AND CONDUCTORS WITH DETUNING PENDULUMS*
- *AMPLITUDES SHOWN DIVIDED BY SAG TO NORMALIZE DATA FROM DIFFERENT SPAN LENGTHS*
- *MAXIMUM GALLOPING AMPLITUDE REDUCED TO ~1/3*

CONTROL OF GALLOPING

TORSIONAL DEVICES

- *DETUNING PENDULUMS FOR TWIN BUNDLES*
- *THREE OR FOUR PER SPAN (AT 1/5, 1/3, 7/12, 3/4 POINTS)*
- *UNITS MOUNTED ON A RIGID SPACER*
- *PREFORMED ROD AND ELASTOMER LINING ATTACHMENTS TO REDUCE LOCAL STRESSES IN CONDUCTOR*



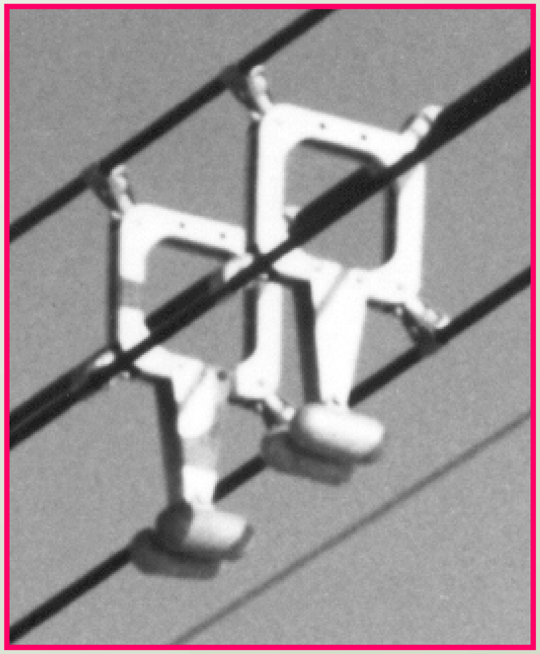
DATA FROM 24 FIELD OBSERVATIONS ON TWIN BUNDLES

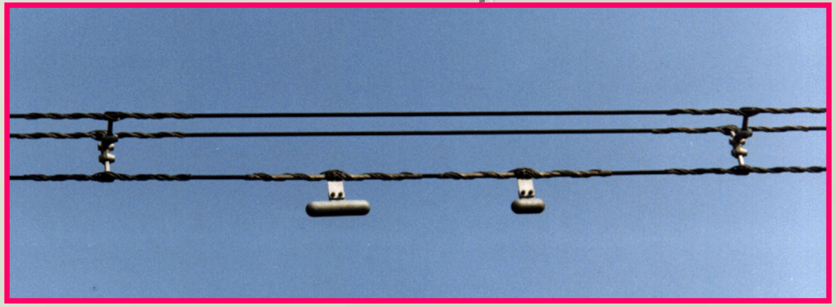
- *MAXIMUM GALLOPING AMPLITUDE REDUCED TO ~1/4*

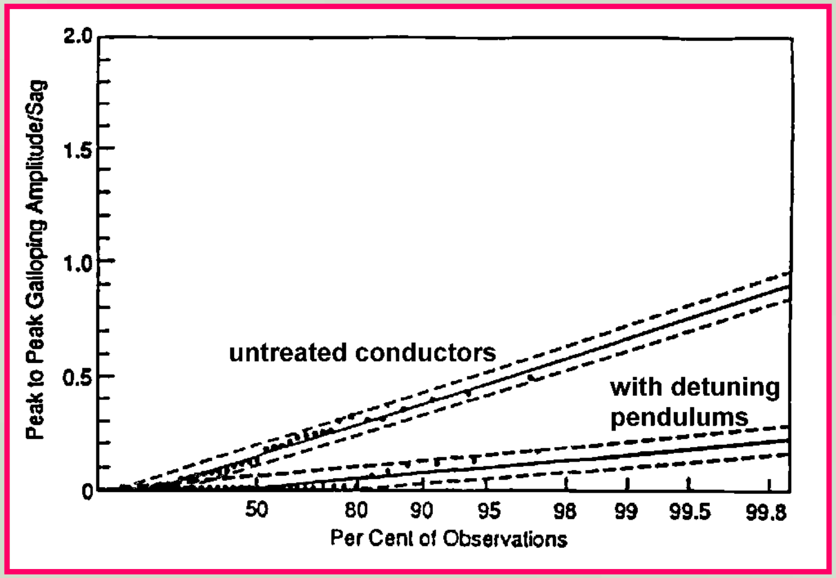
CONTROL OF GALLOPING

TORSIONAL DEVICES

- *DETUNING PENDULUMS FOR TRIPLE AND QUAD BUNDLES*
- *UNITS MOUNTED ON A SPACER DAMPER OR ON LOWER SUBCONDUCTOR W ITH EXTRA SPACERS TO MAINTAIN BUNDLE GEOMETRY*
- *ARM LENGTH LIMITED BY CORONA PERFORMANCE*



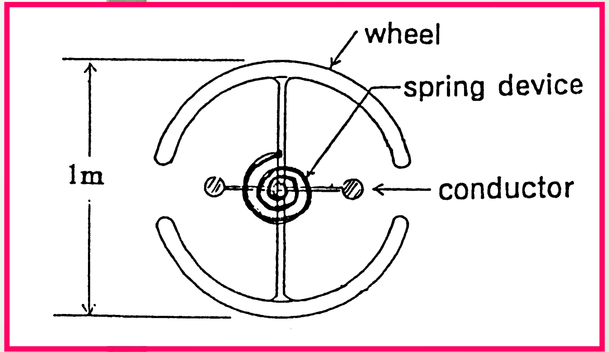


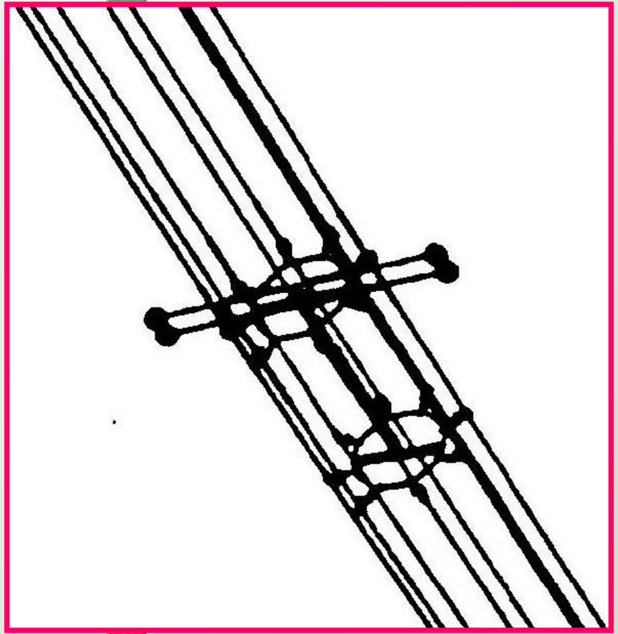


DATA FROM 32 FIELD OBSERVATIONS ON QUAD BUNDLES

- *MAXIMUM GALLOPING AMPLITUDE REDUCED TO ~1/4*

CONTROL OF GALLOPING





TORSIONAL DEVICES WITH DAMPING

- *TCD (Japan)*
- *TORSIONAL TUNER AND DAMPER (GCD, JAPAN)*
- *TORSIONAL DAMPER AND DETUNER (TDD, BELGIUM)*

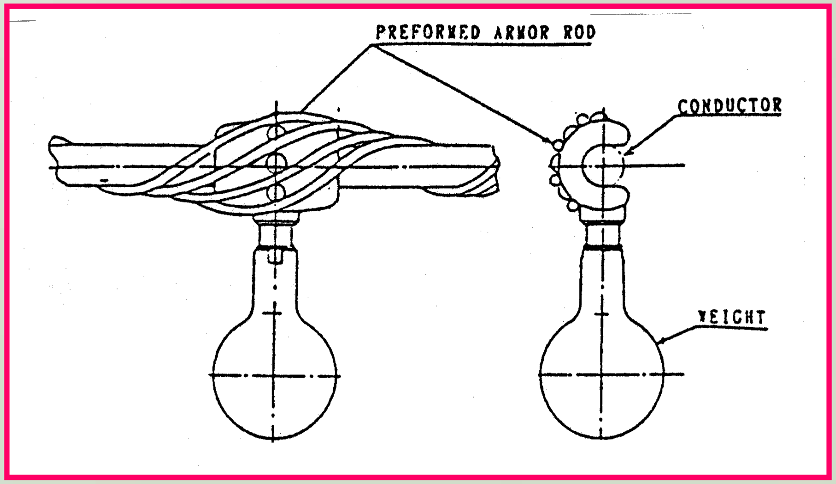
- *USUALLY TWO UNITS PER SPAN - DESIGNED TO MATCH SINGLE LOOP AND TWO LOOP GALLOPING FREQUENCIES*

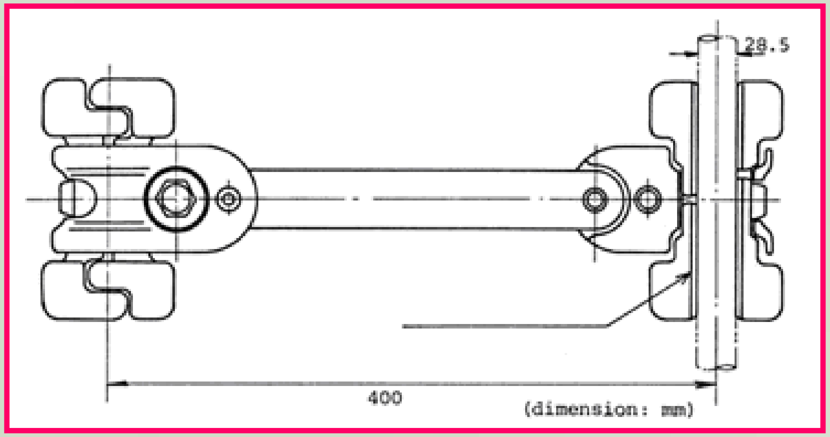
- *ALL TORSIONAL DEVICES ARE DESIGNED SPECIFICALLY FOR THE CONDUCTOR SIZE, SPAN LENGTH AND TENSION OF THE PARTICULAR SPANS TO WHICH THEY ARE ATTACHED*

CONTROL OF GALLOPING

ECCENTRIC WEIGHTS (GCD) AND ROTATING CLAMP SPACERS (JAPAN)

- *GALLOPING IS REDUCED WHEN THE ICE PROFILE IS SMOOTH AND LESS ECCENTRIC*
- *DEVICES ENCOURAGE CONDUCTOR OSCILLATION DURING ICE STORMS*
- *USED FOR WET SNOW EXPOSURE*
- *THE ECCENTRIC WEIGHTS ARE ABOUT 20 KG, AND ARE MOUNTED HORIZONTALLY IN ALTERNATING DIRECTIONS ON THE SUBCONDUCTORS*
- *SYSTEM APPLIED TO SINGLE CONDUCTORS AND TWIN AND QUAD BUNDLES*

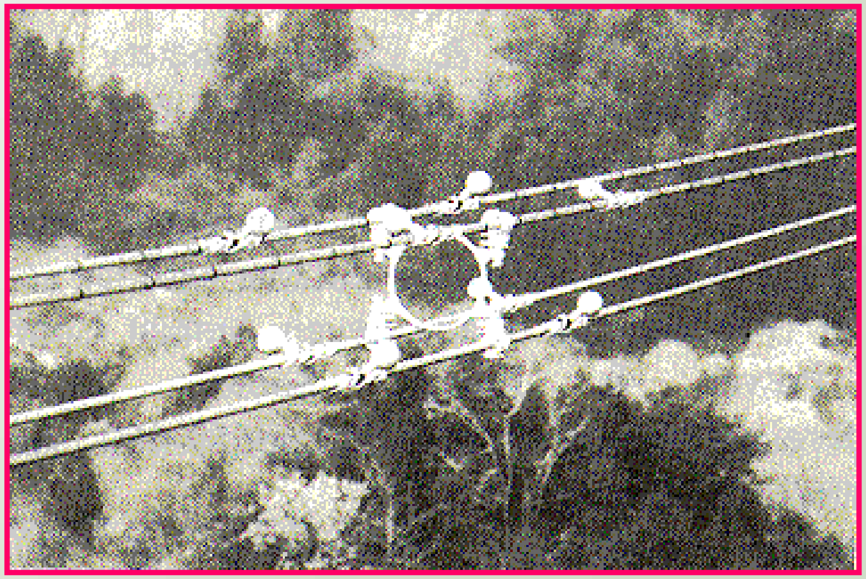


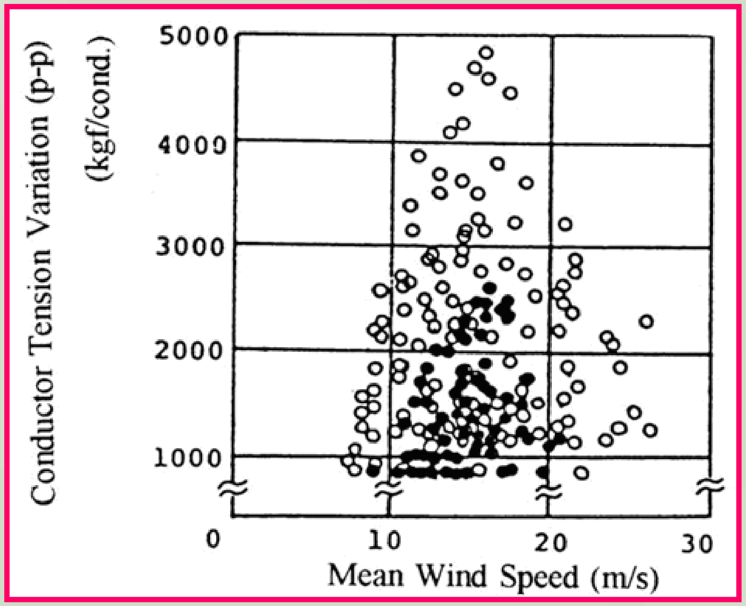


CONTROL OF GALLOPING

ECCENTRIC WEIGHTS (GCD) AND ROTATING CLAMP SPACERS (JAPAN)

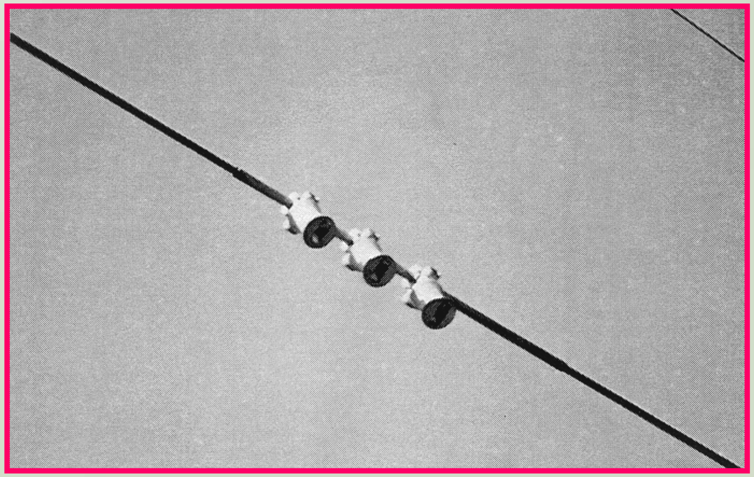
- *FIELD TRIALS SHOW REDUCED TENSIONS WITH GCD*
- *SYSTEM APPLIED TO SINGLE CONDUCTORS AND TWIN AND QUAD BUNDLES*





CONTROL OF GALLOPING

AR TWISTER (USA)



- *AR TWISTER IS DESIGNED TO CREATE A SMOOTH ICE PROFILE ON SINGLE CONDUCTORS*
- *THIS DEVICE IS A WEIGHT ATTACHED RIGIDLY TO THE CONDUCTOR BY A STANDARD CONDUCTOR CLAMP*
- *THE INDIVIDUAL WEIGHTS ARE ABOUT 3.6 KG (8 LB)*
- *THEY ARE INSTALLED VERTICALLY ABOVE THE CONDUCTOR AT MID-SPAN, AND THE TOTAL WEIGHT AND NUMBER OF DEVICES IS CHOSEN TO ROTATE THE CONDUCTOR BETWEEN 90 AND 140 DEGREES*
- *DURING GALLOPING THE ROTATIONAL OSCILLATIONS ARE ENHANCED, AND THE ICE DEPOSIT IS SMOOTHER AND THINNER*
- *THE AERODYNAMIC LIFT IS THEREBY REDUCED AND GALLOPING IS LESS LIKELY TO OCCUR.*

CONTROL OF GALLOPING

SUMMARY OF GALLOPING CONTROL DEVICES (1/3)

DEVICE NAME	APPL'N	WEATHER CONDITION		LINE CONSTRUCTION			COMMENTS
		GLAZE	WET SNOW	DIST'N	SINGLE TRANS'N	BUNDLE	
RIGID AND FLEXIBLE INTERPHASE SPACERS	WIDELY USED	YES	YES		YES	YES	PREVENTS FLASHOVERS, NOT GALLOPING MOTIONS
AIR FLOW SPOILER	WIDELY USED	YES		YES	YES	YES	COVERS 25% OF SPAN LIMITED BY VOLTAGE EXTENSIVE FIELD EVALUATION
ECCENTRIC WEIGHTS & ROTATING CLAMP SPACERS	USED IN JAPAN		YES		YES	YES	THREE PER SINGLE SPAN ONE PER SPACER PER SUB-CONDUCTOR

CONTROL OF GALLOPING

SUMMARY OF GALLOPING CONTROL DEVICES (2/3)

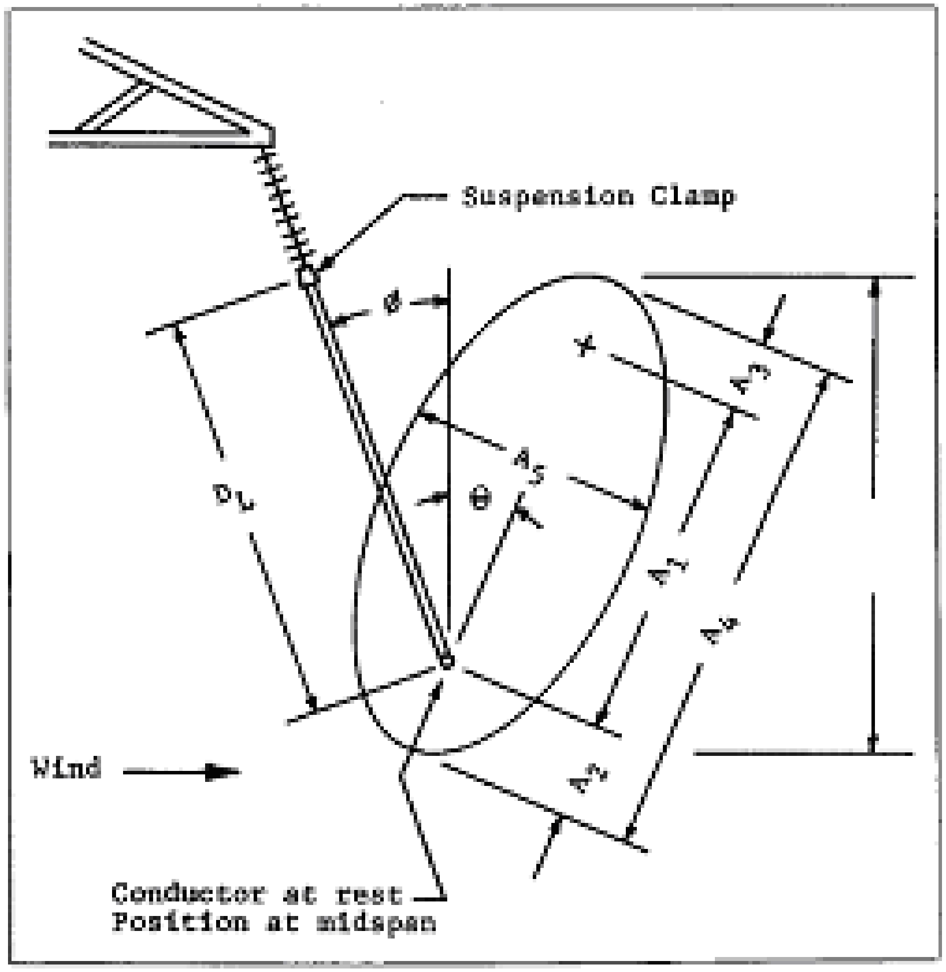
DEVICE NAME	APPL'N	WEATHER CONDITION		LINE CONSTRUCTION			COMMENTS
		GLAZE	WET SNOW	DIST'N	SINGLE TRANS'N	BUNDLE	
AR TWISTER	USED IN USA	YES			YES	YES	TWO PER SPAN
AR WINDAMPER	USED IN USA	YES			YES	YES	TWO PER SPAN
TORSIONAL CONTROL DEVICE (TCD)	USED IN JAPAN		YES			YES	TWO PER SPAN

CONTROL OF GALLOPING

SUMMARY OF GALLOPING CONTROL DEVICES (3/3)

DEVICE NAME	APPL'N	WEATHER CONDITION		LINE CONSTRUCTION			COMMENTS
		GLAZE	WET SNOW	DIST'N	SINGLE TRANS'N	BUNDLE	
GALLOPING CONTROL DEVICE (GCD)	USED IN JAPAN		YES			YES	TWO PER SPAN
DETUNING PENDULUM	WIDELY USED	YES		YES	YES	YES	3 OR 4 PER SPAN. USES ARMOR RODS IF TENSION IS HIGH. MOST EXTENSIVE FIELD EVALUATIONS
TORSIONAL DAMPER AND DETUNER (TDD)	EXPER-IMENTAL	YES				YES	2 OR 3 PER SPAN

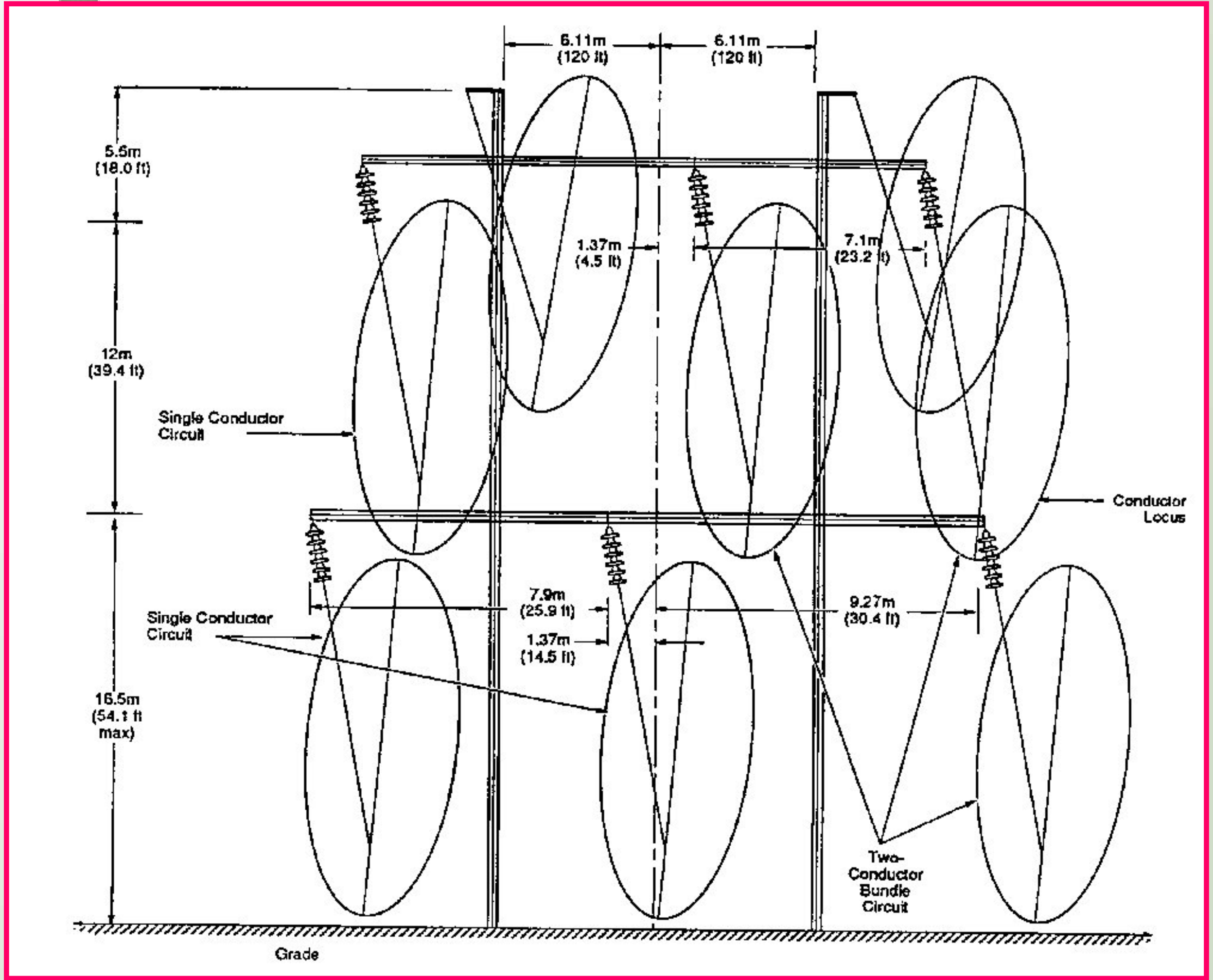
DESIGN AGAINST GALLOPING



RURAL ELECTRIFICATION ADMINISTRATION (REA) GUIDE

- *COMMON DESIGN METHOD IS ELLIPTICAL CLEARANCE ENVELOPE - BASED ON 1930S TECHNOLOGY*
- *ANGLE OF ELLIPSE RELATED TO SWING ANGLE OF CONDUCTOR*
- *ASSUMES MOTIONS LIMITED TO ~1.3 x SAG ON SPANS SHORTER THAN 230 m*
- *VERTICAL HEIGHT BASED ON MULTIPLE LOOP GALLOPING ON SPANS LONGER THAN 230m*

DESIGN AGAINST GALLOPING



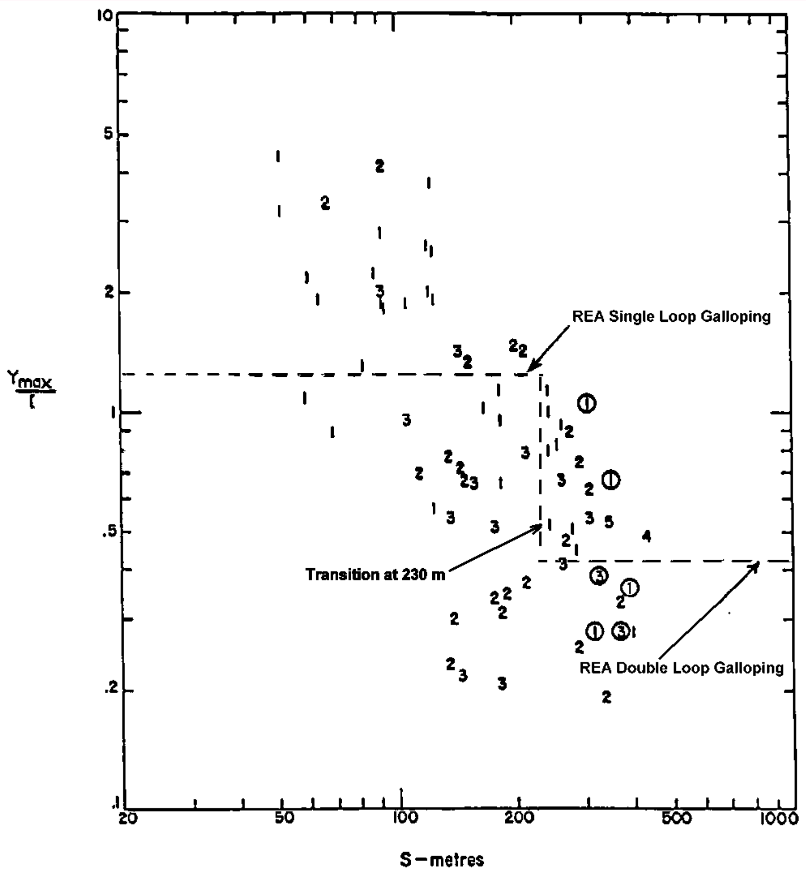
GALLOPING CLEARANCE ELLIPSES FOR A STRUCTURE

- ***STRUCTURE HAS TWO CIRCUITS AND TWO OVERHEAD GROUND WIRES***
- ***ELLIPSE OVERLAPS SHOW FLASHOVER POINTS DURING GALLOPING***
- ***AIR GAP REQUIRED BETWEEN ELLIPSES BASED ON VOLTAGE OF LINE***

PHASE TO PHASE AND PHASE TO GROUND CLEARANCES REQUIRED BETWEEN GALLOPING CLEARANCE ELLIPSES

Voltage	115 kV	138 kV	230 kV	345 kV	500 kV
Phase-Phase	0.46 m (1.5 ft)	0.46 m (1.5 ft)	0.76 m (2.5 ft)	1.07 m (3.5 ft)	1.83 m (6.0 ft)
Phase-Ground	0.30 m (1.0 ft)	0.30 m (1.0 ft)	0.61 m (2.0 ft)	0.76 m (2.5 ft)	1.22 m (4.0 ft)

DESIGN AGAINST GALLOPING

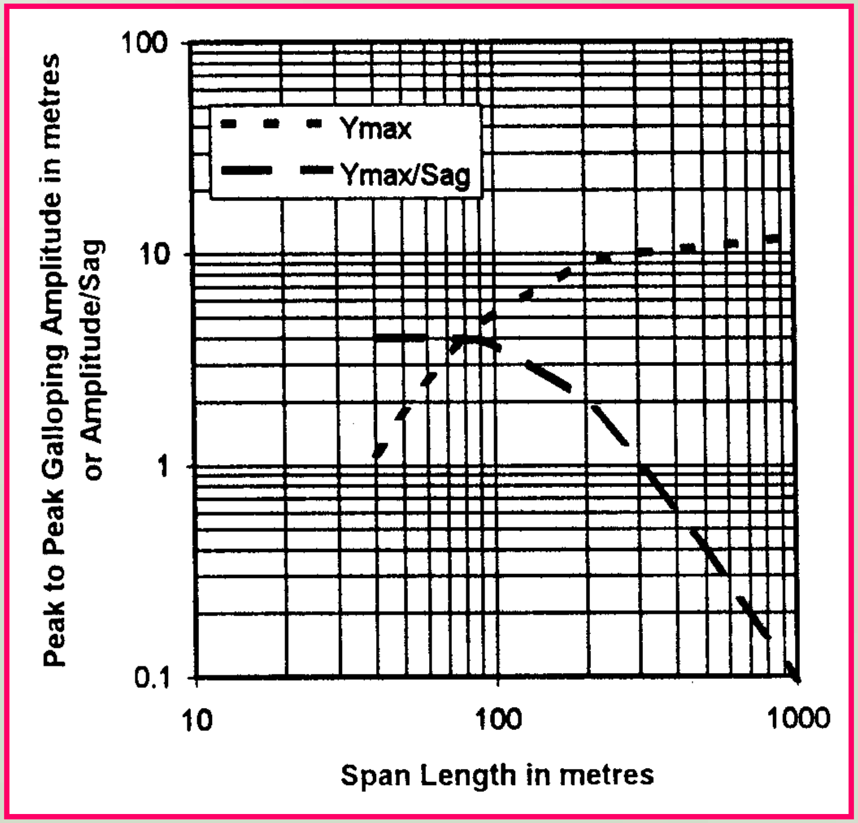


PEAK TO PEAK GALLOPING AMPLITUDE / SAG vs SPAN LENGTH FROM FIELD DATA AND CORRESPONDING REA GUIDE

- *FIELD DATA ON GALLOPING SHOW DEFICIENCIES IN ASSUMED GALLOPING MOTIONS*
- *DIFFERENCE BETWEEN GALLOPING DUE TO GLAZE ICE AND WET SNOW NEEDS TO BE RECOGNIZED*
- *DYNAMIC LOADS DUE TO GALLOPING ARE NOT EXPLICITLY INCLUDED*
- *DESIGN APPROACH NEEDS UPDATING BASED ON PRESENT KNOWLEDGE*

DESIGN AGAINST GALLOPING

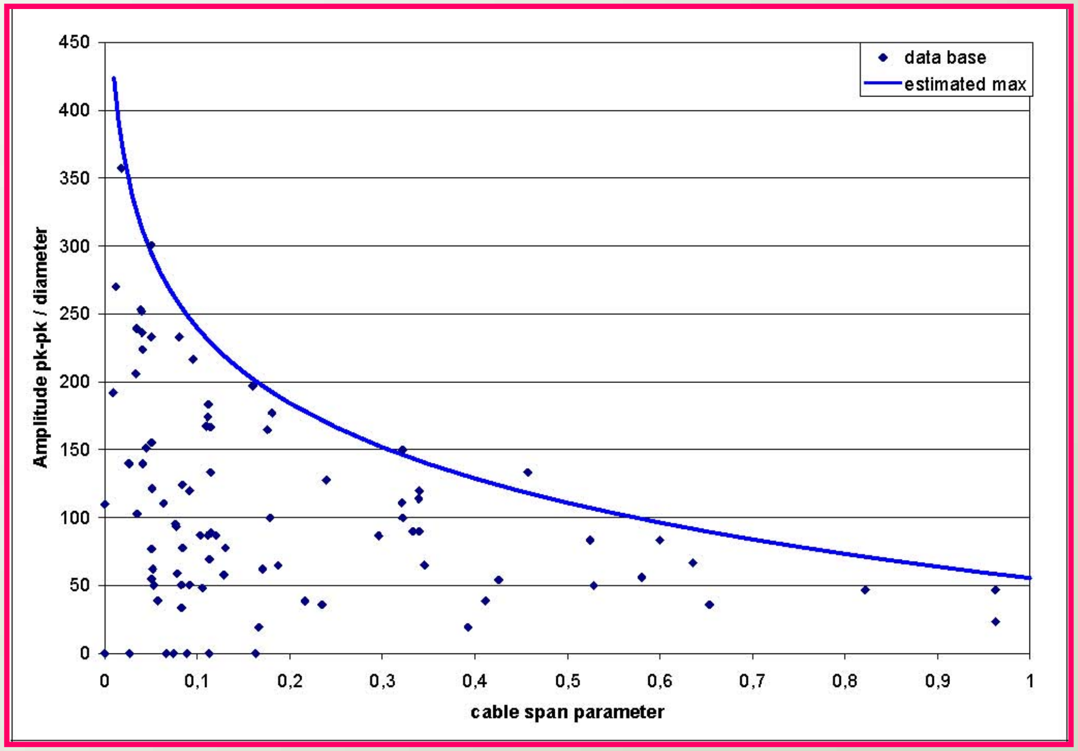
- *BASED ON ANALYSIS OF FIELD DATA FROM ALL GALLOPING OBSERVATIONS*
- *DATA FROM SINGLE CONDUCTOR SITES ONLY*
- *BUNDLE DATA IS FOR LONGER SPANS LENGTHS ONLY*
- *SIMILAR ENVELOPES OF MAXIMUM AMPLITUDE AND AMPLITUDE/SAG FOR BUNDLE CONDUCTORS*



MAXIMUM GALLOPING AMPLITUDE AND AMPLITUDE/SAG VERSUS SPAN LENGTH

- *ENVELOPES OF FIELD DATA*

DESIGN AGAINST GALLOPING



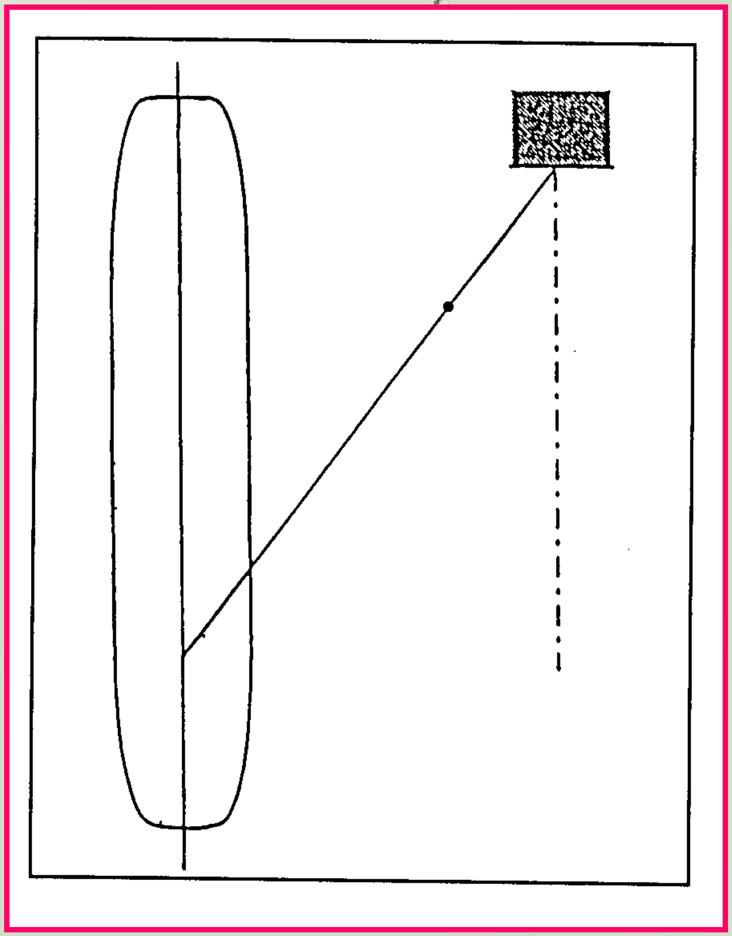
CABLE SPAN PARAMETER = 100 X DIAM / 8 X SAG

FITTED CURVE: A/D = 80 LN (8 X SAG / 50 X DIAM)

- *ALTERNATIVE CURVE OF MAXIMUM GALLOPING AMPLITUDES WITH BETTER FIT TO THE DATA*
- *AMPLITUDE/DIAMETER VS CABLE SPAN PARAMETER*
- *SAME CURVE FOR SINGLE AND BUNDLE CONDUCTORS*
- *DATA ARE FOR GLAZE ICE CONDITONS*
- *MORE DATA ARE NEEDED FOR GALLOPING DUE TO WET SNOW*

ALTERNATIVE GALLOPING ENVELOPE

- *BASED ON FRAME BY FRAME ANALYSIS OF 44 MOVIE FILMS OF GALLOPING FROM SINGLE AND TWIN, TRIPLE, AND QUAD BUNDLE LINES*
- *ALL GALLOPING EVENTS FILMED WERE DUE TO GLAZE ICE*
- *MOTIONS ARE ALMOST ENTIRELY VERTICAL*
- *WIDTH OF ENVELOPE IS 20 PERCENT OF HEIGHT*
- *UPWARD MOVEMENT IS 3 TIMES AS LARGE AS DOWNWARD MOVEMENT FROM STATIC POSITION*



ENVELOPE OF GALLOPING MOTIONS BASED ON FILM ANALYSIS

CONCLUSIONS (1 OF 2)

- *GALLOPING ON POWER LINES MAY INDUCE SERIOUS DAMAGE ON ALL PARTS*
- *OCCURRENCES ARE DIFFICULT TO PREDICT BECAUSE THEY DEPEND ON THE ICE SHAPE AND DENSITY, WIND SPEED AND DIRECTION, AND DYNAMIC STRUCTURAL PROPERTIES, SUCH AS NATURAL FREQUENCY AND STIFFNESS OF THE CONDUCTOR UNDER THE ICE AND WIND CONDITIONS*
- *GALLOPING IS A COMPLEX AEROELASTIC INSTABILITY*
- *CONTROLS FOR PREVENTING GALLOPING ARE MAKING PROGRESS*

CONCLUSIONS (2 OF 2)

- ***THE TWO MECHANISMS OF GALLOPING NEED DIFFERENT MEANS OF PREVENTION***
- ***DIFFERENT ICE AND WET SNOW CONDITIONS NEED DIFFERENT TREATMENT***
- ***SINGLE AND BUNDLE CONDUCTORS NEED DIFFERENT TREATMENT***
- ***DESIGN ELLIPSES CAN BE USED FOR CLEARANCES AND TOWER CAN BE DESIGNED TO RESIST THESE EXCEPTIONAL EVENTS***
- ***NEW INFORMATION IS AVAILABLE TO UPDATE DESIGN CLEARANCES FOR SOME CONDITIONS***

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