An Investigation Into The Aerodynamic Characteristics of Catenary Contact Wires in a Cross-Wind.

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An experimental analysis of the aerodynamic characteristics of Catenary contact wires is presented. The aerodynamic data obtained was used to calculate the Glauert-Den Harthog criterion for one dimensional galloping. Utilising this criterion the susceptibility to galloping instability of a number of contact wire cross sections was assessed. The analysis showed that a galloping oscillation can only be induced, into the contact wires tested, in a strong wind when the wire is worn and the flow approaches the wire at an angle of between 7 and 14 degrees to the horizontal. This analysis provided an explanation for the large scale oscillations experienced by Catenary wires on the elevated railway tracks position in exposed positions where the close proximity of the embankment to the wire generates large angles of attack in the flow field around the contact wire.

NOTATION

α	angle of incidence
ρ	density
m	mass per unit length
y	displacement
ξ	damping ratio
ω_1	natural circular frequency
B	diameter of wire
C_L	lift coefficient
C_D	drag coefficient
d	damping coefficient
U	velocity
u_*	shear velocity
ν	kinematic viscosity
x	horizontal coordinate
y	vertical coordinate

1. INTRODUCTION

It has been known, for an extended period of time, that there are problems associated with large amplitude oscillations, in the overhead conductors at a number of locations on the East and West coasts of Scotland. The oscillating conductors have the potential to cause a serious dewirement between the contact wire/pantograph interface leading to the delay and cancellation of services using the effected lines. In all cases it has been determined that in high winds the conductors display an aerodynamically induced, large amplitude, oscillation. Analysis of video film of these oscillations would indicate that the oscillations are created by a phenomenon known as galloping. Galloping is created by unsteady wind forces acting on an object. The unsteady forces are caused by the shape of the object generating asymmetric lift and drag forces which produce an undamped oscillation. A typical conductor contact wire has a cylindrical shape with two grooves as shown in figure 5. An alternative contact wire also has a small groove running along the top of the contact wire also shown in figure 5. It was thought that the sharp edges of these grooves produce a defined separation point which, when coupled with a heaving and pitching motion of the wire, produces the aerodynamic galloping phenomenon observed. For more information on this subject the reader is referred to Sachs [1] and Simiu [2]. The authors initially considered wind breaks and shelter belts as a palliative to the galloping instability and the results of this work can be found in Scanlon et al [3]. However, due to physical constraints around typical embankments it is often not practical to construct the shelter belts suggested. This caused a review of the manner in which the oscillations might be reduced. It was considered that the galloping phenomenon might be reduced by;

1. Modification of the contact wire cross section.
2. Generation of mechancial damping forces.

This study has been undertaken to see if it is possible to reduce the galloping experienced by the catenary contact wires by slight modifications to the profile of the contact wire.

1.1 One Dimensional Aerodynamic Galloping

Consider a simple wing in a wind tunnel. If the forces acting on the wing are measured as the angle between the wing and the free stream (the angle of incidence, α) is gradually increased, while the wind speed is held constant, then a graph of lift against incidence may be plotted, shown in figure 2.

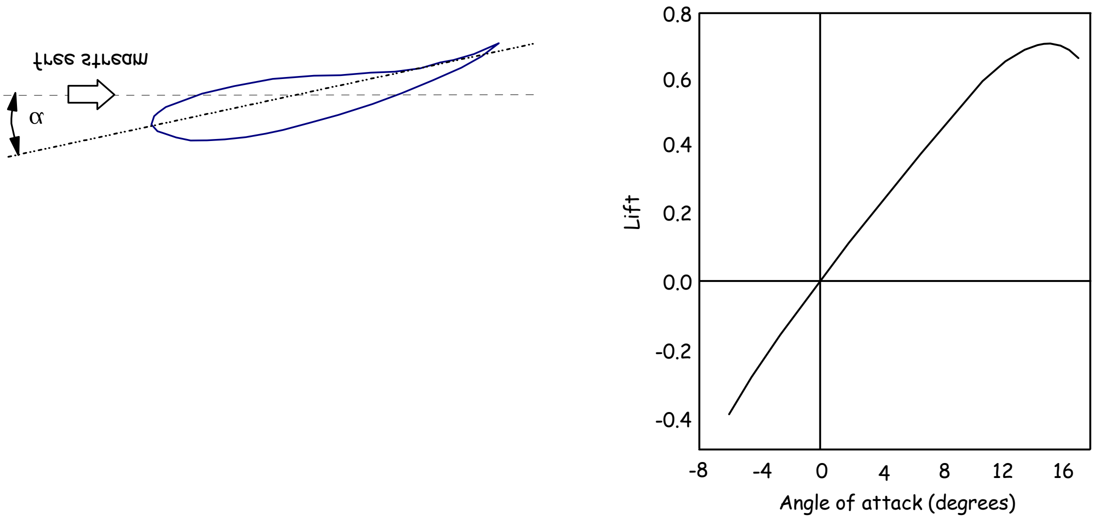

Figure 1: lift curve for a wing

From figure 1, it may be seen that, as the incidence is increases the lift force increases almost linearly until about 15^{o} whereupon the boundary layer separates and the wing stalls. However between about -4^{o} and 12^{o} the slope of the line is constant and positive. In this hypothetical experiment the angle of incidence has been increased slowly and it may be considered that the wing has been stationary at a fixed angle of attack when the force was measured. Now consider the case of a wing at 0^{o} angle of attack but suddenly moved in the upward direction as shown in figure 2.

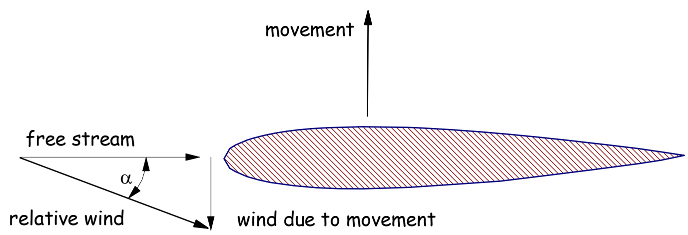

Figure 2: Motion induced change in angle of attack

The upward motion generates a downward component of wind which, when combined with the free stream velocity generates a negative angle of attack on the wing where before it was zero. Now, referring to the graph in figure 1 it may be seen that this negative angle of attack will generate a negative lift force which is downward, against the direction of motion, hence this is a restoring force and the system is stable. Any displacement will generate a force that opposes the motion. However, consider the case of a shape which generates a lift curve as shown in figure 3.

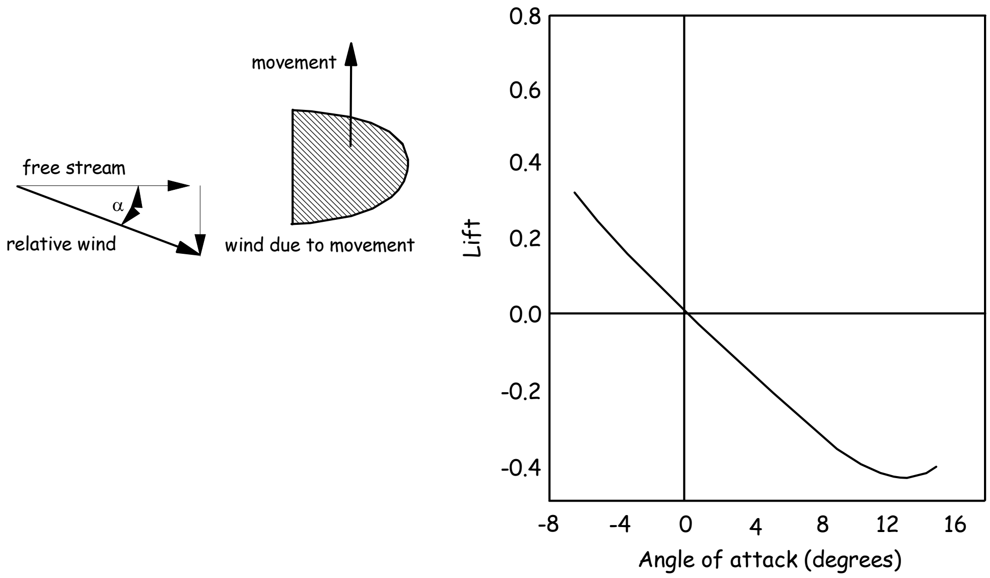

Figure 3: Lift curve for galloping section

In this case when the object moves upward from a zero angle of incidence and generates a negative angle of incidence it creates a positive lift force which is in the direction of motion which will cause the displacement to increase - an unstable situation. This is known as a galloping instability due to the destructive nature of the phenomenon which leads to large amplitude oscillations which can be divergent.

The galloping instability described above is one dimensional galloping where the change in the angle of incidence is due to the up and down motion of the object in one dimension. However, the change in the angle of incidence can also be caused by the twisting of the object and by a combination of the two if the object can sway in a pendulum like motion in the wind. For information on two and three dimensional galloping the reader is referred to the works of Li et al[4], Matsumoto et al[5], and Chabart et al[6]. In the case of the OLE conductor system under consideration it is thought that the cause of the large amplitude oscillations were due primarily to one dimensional galloping. If it was due to twisting or pendulum galloping it would be more prevalent over the entire rail network.

Mathematically it is possible to determine whether or not an object is likely to suffer from a one dimensional galloping instability by the Den Harthog criterion. Simiu[1] derives the equation of 1D motion of an object in a steady wind.

$$m\left[\ddot{y} + 2\zeta\omega_1\dot{y} + \omega_1^2 y\right] = -\tfrac{1}{2}\rho U^2 B\left(\frac{dC_L}{d\alpha} + C_D\right)_0 \frac{\dot{y}}{U}\zeta \tag{1}$$

where the right hand side of the equation is the aerodynamic contribution to the overall system damping. Rearranging this equation gives the net damping coefficient, d, as:

$$2m\zeta\omega + \tfrac{1}{2}\rho UB\left(\frac{dC_L}{d\alpha} + C_D\right)_0 = d \tag{2}$$

If this damping coefficient is positive the system is stable and if it is negative the system is unstable. Since the mechanical damping ratio, ζ, is usually positive then a system cannot gallop unless:

$$\left(\frac{dC_L}{d\alpha} + C_D\right)_0 \prec 0 \tag{3}$$

which is referred to as the Glauert - Den Hartog criterion.

It should be noted that a system will not gallop unless d < 0 and this will depend upon the above criterion being met, that the mass and mechanical damping ratio are sufficiently small and the wind speed U to be sufficiently high for d to be negative. When all these conditions are met then a galloping instability will occur.

The following experimental work was carried out to determine the value of the Glauert - Den Hartog criterion for the section of the contact wire of the OLE conductors. It is recognised that there are two principle components of the overhead conductors, the helical wound suspension catenary wire and the grooved contact wire. But, as the suspension catenary wire is helical wound for a long length, such as found between the masts of the overhead conductor, this would not be affected by different inclinations of the free stream. Although this shape of wire is known to be capable of galloping if it was the cause of the galloping on the elevated sections of track then it should be expected that the overhead conductor would gallop across the whole network and, fortunately, this is not the case. Attention was therefore paid to the contact wire and the Den Hartog criterion for the section measured in a wind tunnel

2. EXPERIMENTAL CONFIGURATION AND INSTRUMENTATION

Scale models ten times the size of the contact wire were tested on the three component, under floor, balance in the closed return, low speed, wind tunnel at the University of Strathclyde, figure 4. The under floor balance is capable of measuring lift, drag and pitching moment. Data is acquired by the manual adjustment jockey weights. The low speed tunnel has an open working section of 1.2m diameter and a maximum speed of 50 m/s with a minimum wind speed of approximately 7 m/s. Turbulence intensity is of the order 1%. The sections tested were 850 mm wide and of 124mm diameter. Constructed from glass fibre covered foam core with a central metal support and flat metal end plates. The flat metal end plates were inteded to reduce the three dimensional nature of the flowfield and generate data simulating the two dimensional wire section. It was considered that the end plates, aligned with the flow would only generate a drag force due to skin friction and little pressure drag. The skin friction drag would be negligible when compared to the pressure drag of the section under test. The support struts were faired in order to minimise their effect on the drag and lift data. Only the last five 5cm of the support strust were in the flow and, again the drag force generated by the strut ends was considered to be small compared to the pressure drag of the section under test. Tests were carried out at 16 m/s giving a nominal Reynolds number of the test as 160,000. The full scale Reynolds number of the contact wire, at 16 m/s wind is 16,800. Whilst it was recognised that the Reynolds number of the test approached the critical Reynolds number for a circular cylinder it was not possible to reduce the experimental Reynolds number and be able to obtain a reasonable output from the under floor balance. It was established that the acquired data was repeatable and not significantly affected by changes in Reynolds number over the range 70,000 to 200,000. The experimental setup may be seen in figure 5.

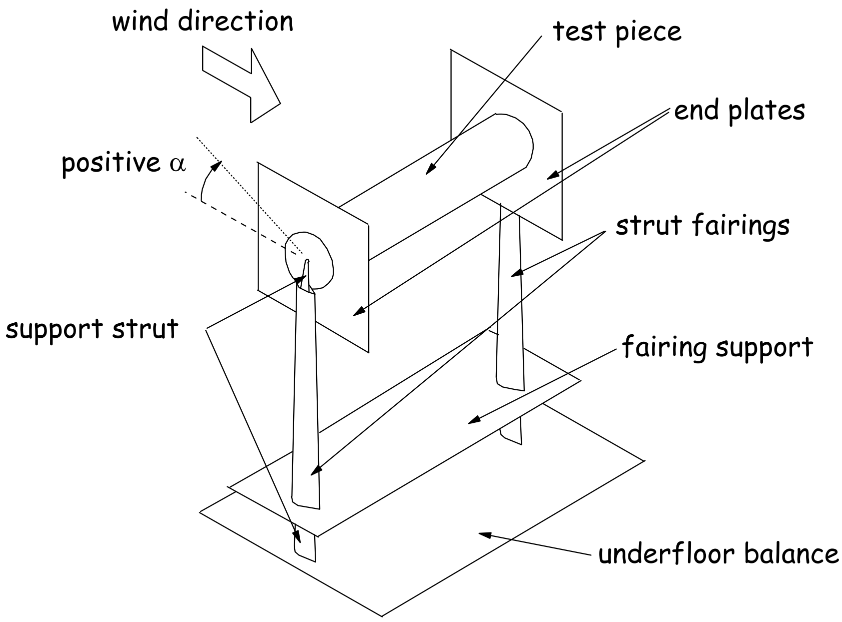

Figure 4: Experimental setup

The lift and drag force were measured for a range of angles of attack $-10^o < \alpha < 20^o$. This allowed the Den Hartog criterion to be calculated over this range of flow angles. As well as the standard contact wire section, with and without a top groove, a number of different sections simulating a worn contact wire as well as wires with rounder lips to the side grooves were tested. A full list of the sections tested may be found in table 1. The dimensions quoted in the text are at model scale and are ten times actual size. A sketch of the listed sections may be found in figure 5.

Without top groove:	With top groove:
▪ Standard section. ▪ 8mm rounded lower lip on the side grooves. ▪ 8mm rounded upper and lower lips on the side grooves. ▪ 22mm flat bottom. ▪ 43mm flat bottom. ▪ 67mm flat bottom. ▪ filled notches.	▪ Standard section. ▪ 43mm flat bottom. ▪ 67mm flat bottom.

Table 1; Wire cross sections tested

Below are the results of these investigations. It should be noted from these graphs that, when the line is in the negative field the section could *possibly* be aerodynamically *unstable* and when it is in the positive field the section *must be* aerodynamically *stable*. Whether or not galloping will occur when the den Hartog criterion is met depends upon the wire mass, the mechanical damping and the wind strength.

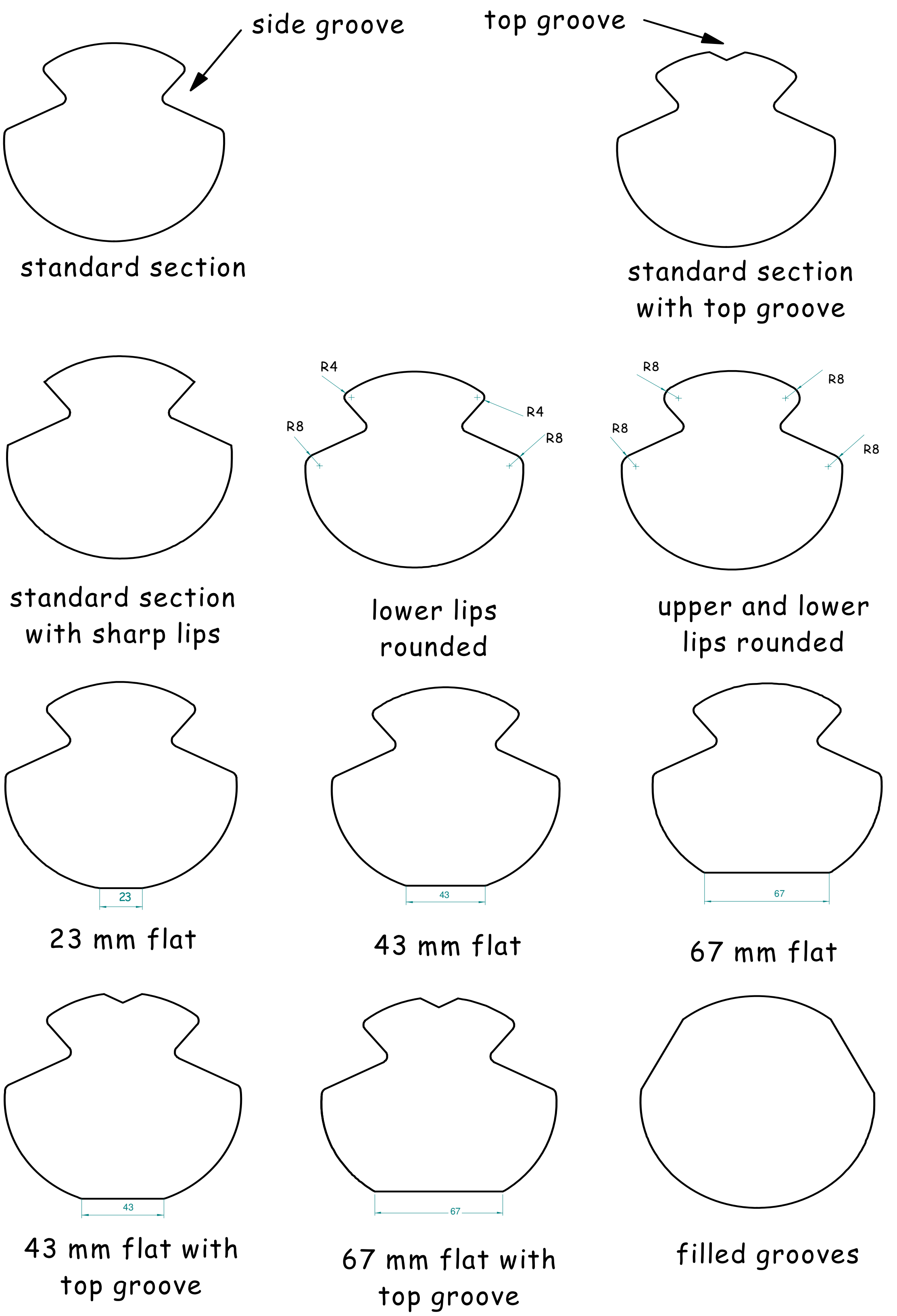

Figure 5: Sketches of sections tested

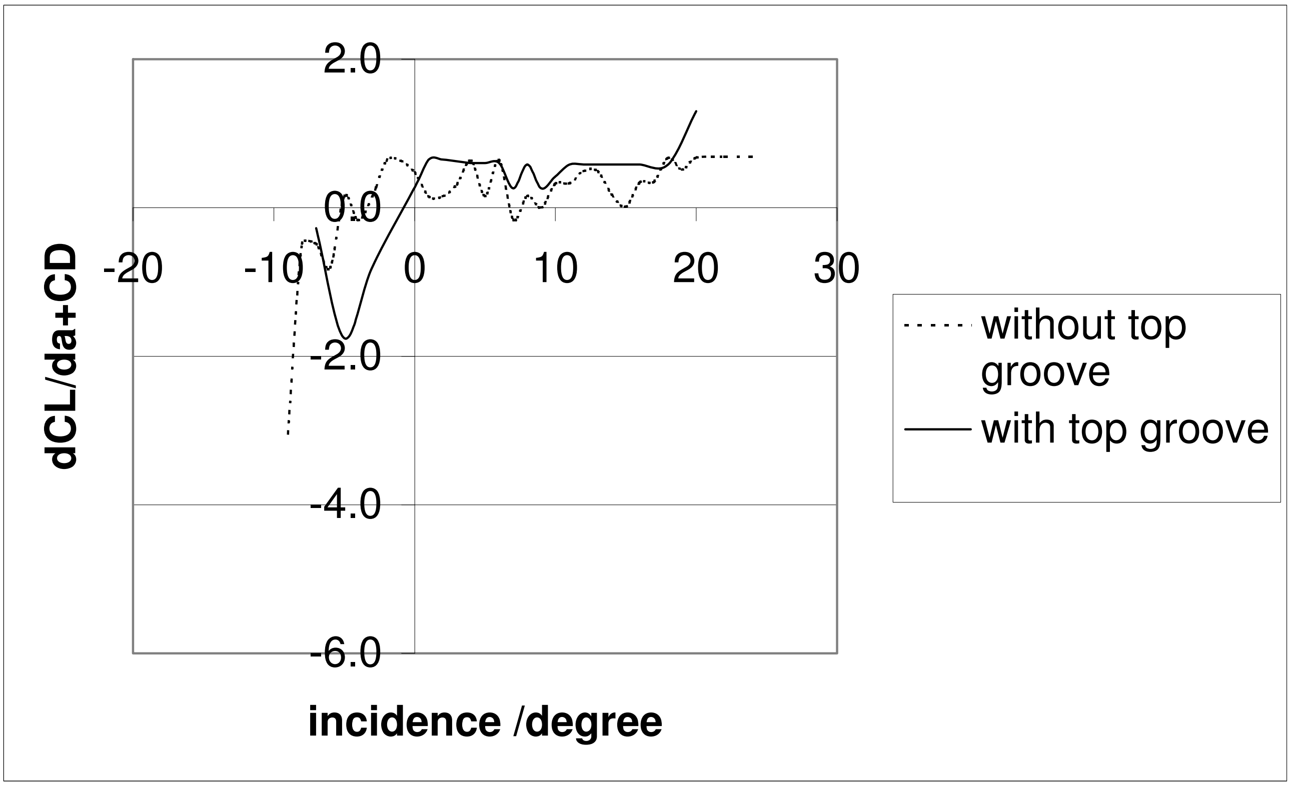

Figure 6: Effect of top groove on standard section

From figure 6, above it may be seen that the standard section, without the top groove, is stable from -6^o to above 20^o below -6^o it may display instability.

The section with the top groove is stable from -1^o to above 20^o with, again, a tendency to instability below -1^o although the trend would indicate that the section is likely to regain stability below -8^o.

It is interesting to note that both sections will not gallop under a positive angle of attack but might gallop if a negative angle of attack, flow from above, was created. It was noted that the contact wire on the upstream wire, on the embankments under consideration, has a high tendency to gallop and, from the previous work of the authors[3], it is unlikely that the upstream wire will experience a negative angle of attack. This would indicate that the contact wire should not gallop whatever the free stream wind speed. However, observation proves this not to be the case.

3. RESULTS AND DISCUSSION

3.1 Effect of wear - no top groove

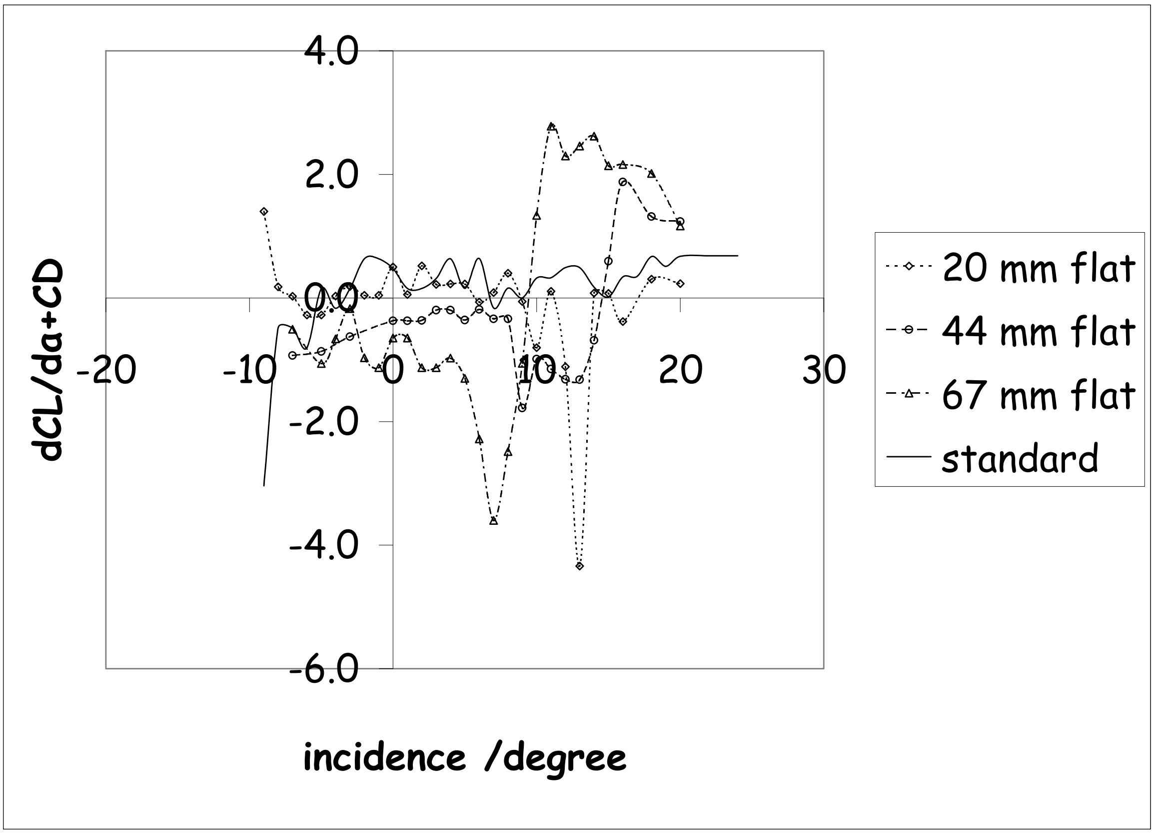

Figure 7: effect of wear- no top groove

The effect of wear on the contact wire was simulated by cutting away the lower surface of the section to generate 20 mm, 44 mm and 67 mm flat sections simulating progressive wear to the contact wire by the passage of the pickup bar on the pantograph.

It may be seen from figure 7 that this wear has a significant effect on the stability of the system. The 20 mm flat section is stable up to about 12^o but then becomes unstable for a couple of degrees. As the wear increases to 44 mm the system becomes slightly unstable over almost the entire range tested with significant tendency to instability between 9^o and 14^o whereupon the system becomes stable above 15^o. If the wear reaches 67mm there is tendency to instability over the lower angles of attack with the angle of attack for significant tendency reduced to 5^o to 10^o whereupon the system again becomes stable.

It may therefore be concluded that the galloping instability of the contact wire is due to the combination of a worn contact area and large angle of attack in high wind due to the large embankment changing the flow angle over the contact wire. As the wire becomes more worn the angle at which galloping may occur will decrease.

3.2 Effect Of Wear - With Top Groove

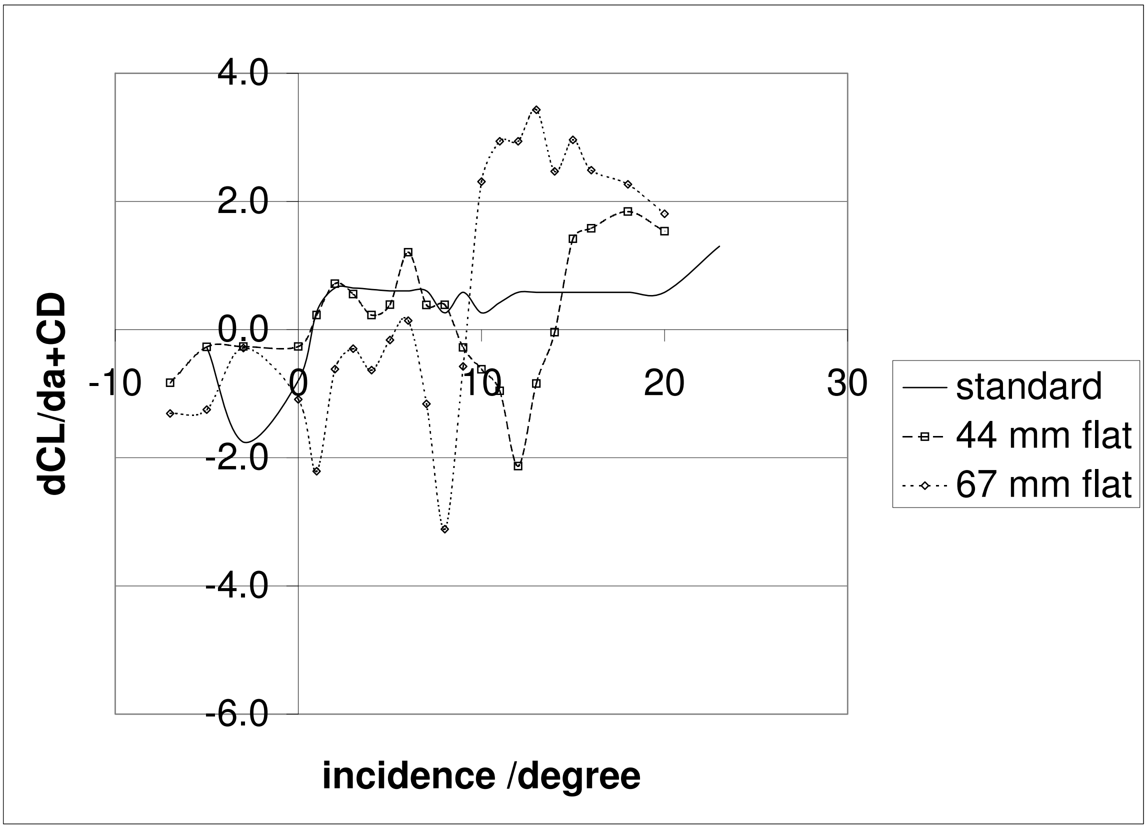

Figure 8: effect of wear - with top groove

The general trend on stability, by wear to the lower surface of the contact wire, when a top groove is included is essentially the same although there would appear to be a slight positive increase to the overall values, figure 8. The increase is only marginal and probably not significant enough to effect whether or not the system would gallop.

3.3 Effect of side grooves

Groove lip rounding

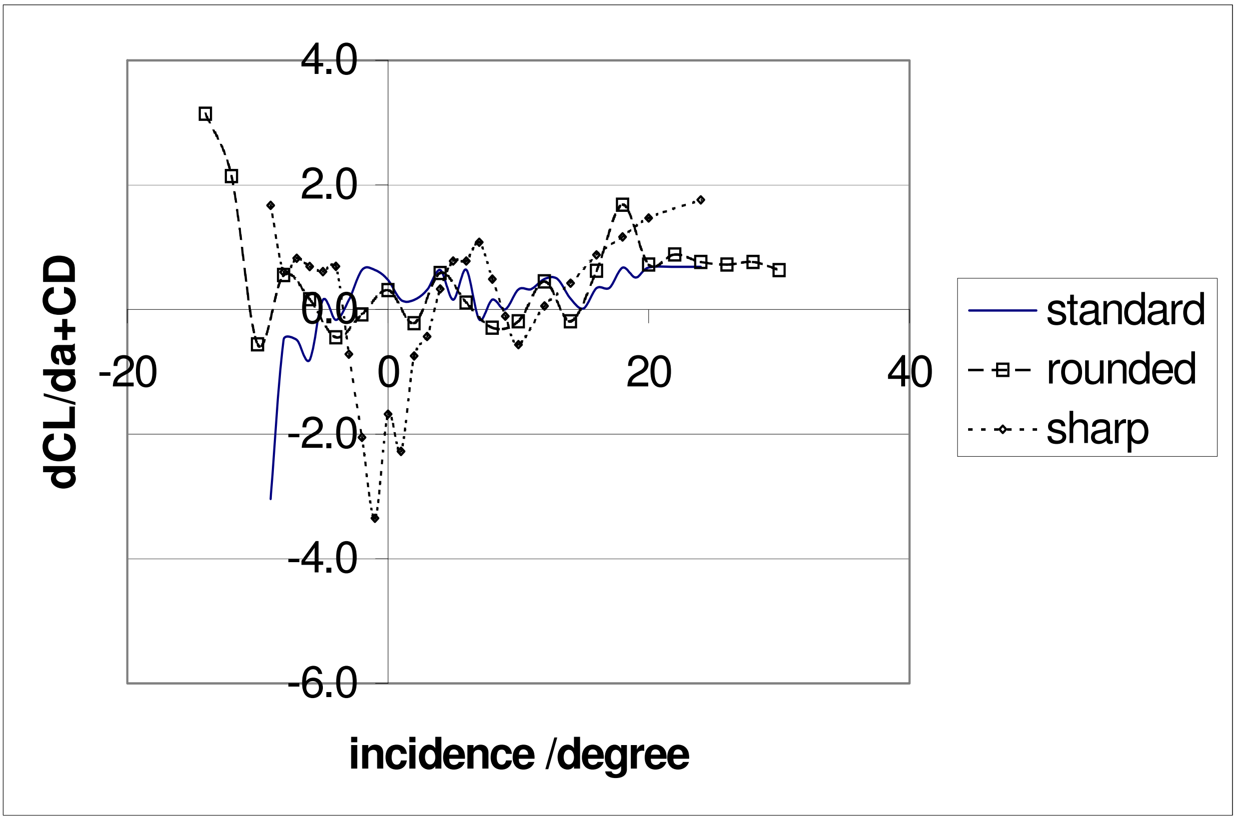

Figure 9: Effect of groove lip shape - no top groove

The lips of the grooves on the standard section have a radius of 4mm. To investigate the effect of increasing this radius to 8mm may be seen above. In general they have little effect apart from making the section more stable at large negative angle of attack. However, as has been stated before, the possibility of this type of flow being experienced by the contact wire is low and therefore there would appear to be no appreciable benefit of rounding these lips.

Removing the radius on the grooves has a significant affect on the stability of the section. This modification generates the possibility of instability between -4° and 4°. This could generate the possibility of galloping over the entire network and it is therefore noted that the outside lips of the side grooves should always be generously radiussed.

Effect of filling side grooves - no top groove

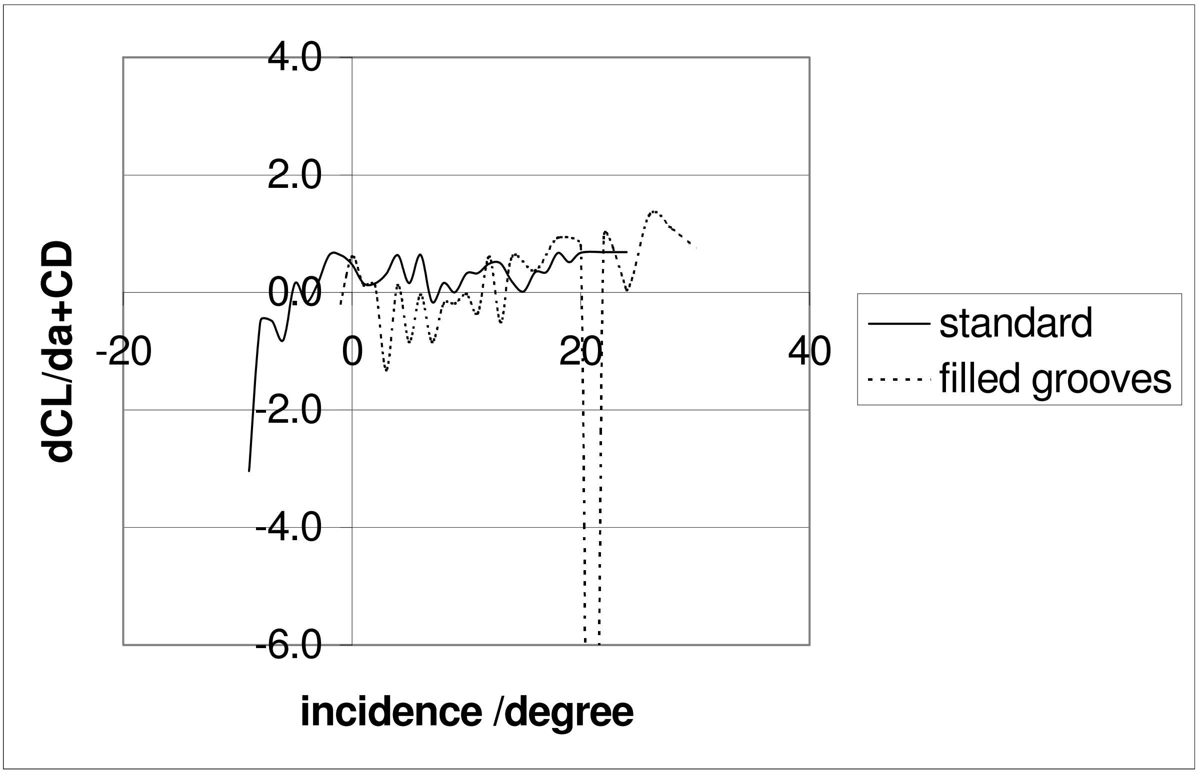

Figure 10: Effect of filling grooves

Although figures 8 and 9 indicated that side grooves were not the cause of the galloping instability a test was conducted to asses whether filling the grooves would create stability . The side grooves were therefore faired in with a simple flat surface.

It may seen from figure 10 that filling the side grooves actually destabilises the system slightly over the majority of the angles tested. It was quite noticeable that they generated a small region of significant instability at 20^{o}. This region of instability was small, only a couple of degrees, but the amount of the instability was significant and it was almost certain that the system would gallop at this incidence.

Thus, filling the side grooves would be prejudicial to the stability of the system and should not be attempted. Also it was noted that generating a flat surface on the contact wire could lead to significant instability. This flattening will occur on the lower surface due to wear between the contact wire and the train pantograph.

3.4 Calculation Of Wind Speed For Galloping

It is interesting, given that the stability parameter has now been measured to calculate the wind speed required for the onset of galloping. The damping in the equation of motion is given by equation 4:

$$2m\zeta\omega + \tfrac{1}{2}\rho UB\left(\frac{dC_L}{d\alpha} + C_D\right) = d \tag{4}$$

rearranging this equation for, U, the wind speed gives:

$$U = \frac{d}{\tfrac{1}{2}\rho B\left(\frac{dC_L}{d\alpha} + C_D\right)} - \frac{2m\zeta\omega}{\tfrac{1}{2}\rho B\left(\frac{dC_L}{d\alpha} + C_D\right)} \tag{5}$$

now, galloping will occur when d is negative hence, if d is set to zero in equation 5 then the value U, wind speed, calculated is the wind speed above which galloping will occur.

$$U = -\frac{2m\zeta\omega}{\tfrac{1}{2}\rho B\left(\frac{dC_L}{d\alpha} + C_D\right)} \tag{6}$$

For this calculation it is assumed that:

$\rho = 1.225$ kg/m^3 (for a 15^{o}C day)

B = 0.496 m^2

m = 38.04 kg

$\xi = 0.1$

$\omega = 1.382$ rad/s

where ω is the natural frequency of a wire stretched between two supports of length, l = 40 m, mass, m = 38.04 kg and tension, T. The tensions of 11,300 N and 17,350 N are the standard tensions in typical contact wires for ambient temperatures of 10^{o}C and -10^{o}C respectively, the natural freuency of a suspended wire can be calculated from equation 7.

$$\omega = \frac{\pi}{l}\sqrt{\frac{T}{m}} \tag{7}$$

Tension N	Frequency rad/s	$\left(\frac{dC_L}{d\alpha}+C_D\right)$	U m/s	U Mph
11300	1.354	-1	33.9	76
11300	1.354	-2	16.95	38
11300	1.354	-3	11.3	25
11300	1.354	-4	8.48	19

Table 2: Wind speed for galloping onset, T=11300N

Tension N	Frequency rad/s	$\left(\frac{dC_L}{d\alpha}+C_D\right)$	U m/s	U Mph
17350	1.677	-1	42	94
17350	1.677	-2	21	47
17350	1.677	-3	14	31
17350	1.677	-4	10	23

Table 3: wind speed for galloping onset, T=17350

From the above it may be seen that it is possible for a galloping instability to occur at wind speeds as low as 20 mph. However, this would only appear to be possible for a lightly worn wire (20 mm flat) over a very small incidence range at about 13^{o}. The more heavily worn wires have a wider range of angles where instability might occur but the value of the instability parameter is much lower ≈ -3 which requires a wind speed > 30 mph for galloping to occur. However, the range of angles for which the instability parameter is –3 is very limited and it is more likely that an instability parameter of –2 will be encountered which has galloping onset at 40 mph. It should be noted that the possibility of galloping is a function of wind speed and flow angle. Therefore even though the above calculations show that it is possible that the system can gallop at a given wind speed the flow angle at the contact wire height is also a function of wind speed. Thus even at extremely high wind speeds it is possible that the flow angle criteria will not be met and the system will not gallop.

3.5 Prevention Of Galloping Instability

To increase the wind speed at which galloping will occur the mechanical damping in the system, ζ, could be increased. The value of 0.1 assumed in the above calculation is for a system with quite high damping already present and is thought to be representative of the damping imparted to the contact wire by the support structure.

The tension in the contact wire and its mass also has an effect on the critical wind speed as they effect the natural frequency of the system, ω, increasing the tension and decreasing the mass will increase the critical wind speed. However, due to the square root in the equation for the natural frequency the tension would need to increase by a factor of 4 to double the critical wind speed and the mass would need to be reduced to a quarter.

4. CONCLUSIONS

It has been shown that the cause of large scale oscillations of contact wires in a high wind is due to one dimensional aerodynamic galloping.

The onset of galloping is due to the combination of:

- High wind
- Flow angle
- Worn wire

Without the combination of all the above three effects the wire will not exhibit 1D galloping.

The range of flow angles at which the wire will gallop is quite narrow and depends upon the wear. If the wire is lightly worn the wire will gallop over a range of only a couple of degrees but at a relatively low wind speed. As the wire becomes progressively more worn the range of flow angles at which the wire will gallop becomes progressively wider but the wind speed for the galloping to occur increases. It is, therefore possible that a heavily worn wire will never exhibit galloping in the usual wind speeds which can be expected.

There are several possibilities for reducing the possibility of galloping

- Increase the tension in the contact wire.
- Decrease the mass of the contact wire
- Increase the mechanical damping
- Shield the contact wire

Increasing the contact wire tension will increase the natural frequency of the wire and hence increase the wind speed for onset of galloping. However the tension will need to be increased four fold for a doubling of the critical wind speed.

Decreasing the mass of the wire will also increase the natural frequency of the wire and increase the critical wind speed. The wire mass would need to be reduced to one quarter of the current mass to double the critical wind speed.

The mechanical damping of the system would linearly increase the critical wind speed. The exact amount is not capable of being determined within the scope of this report. The damping ratio of 0.1 included in the equation for the total damping is fairly conservative and hence some means of significantly increasing the mechanical damping of the system would be required.

It is interesting to note that the gradual wear of the contact wire leads to instability over a wide range of flow angles and, when severely worn, the wire will gallop at all reasonable flow angles in a wind of sufficient strength.

The top groove in general produces a stabilising effect. However it is noticeable that it might generate instability at about 1^{o} angle of attack.

The slight rounding of the lips of the side grooves have a stabilising effect and should be made more rounded if possible. Every effort should me made to ensure that the groove lips are never sharp as this generates a significant destabilising effect.

ACKNOWLEDGEMENTS

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