Towards optimization of ground-powered glider launch

by J. V. Byrne, B. E., University College, Dublin

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1. Introduction

For economic utilization and pilot satisfaction, gliders should be launched into their operational height band. While the trend towards aerotow will undoubtedly continue, many fields are long enough for winchlaunching to over 600 metres and it becomes of interest, first to work towards optimization of the launch for height on a theoretical basis and then to examine the techniques necessary for its practical realization. The point of view is that of the user, who must observe the limits set by the designer to protect the structure.

The flight-path of a somewhat idealised glider is considered for a constant airspeed winch-launch. A digital-computer programme is presented which allows for cable drag and weight, and the numerical results for 21 variations of the parameters are summarised.

Procedures for the control of cable tension and glider speed are put forward. Wire size is shown to become more important as higher launches are attempted, and techniques for using the lightest grades of wire are discussed.

A description is given of the automobile-pulley system developed at Dublin, which combines winch characteristics with very fast cable retrieve.

2. Explanation of method

A loss-free glider could climb steadily, relative to a stationary atmosphere, at right-angles to the applied force F (Fig. 1). The machine considered will fly a path shallower by the gliding angle G.

The applied force F is made up of aircraft weight W and cable pull C. The cable pull C is resolved into components S and B along and perpendicular to the straight line joining the aircraft to the winch.

The aircraft speed V is taken as constant and its maximum value is the permitted winch-launch speed. For any value of V there is a corresponding maximum value for F, designated FM, such that the polar for the loading FM gives minimum sink at the speed V. Higher values of F would stall the glider or give drag/lift ratios worse than the assumed value G.

A separate limitation is given by the maximum cable pull C which can be allowed. Here the aim of the limit CM is to avoid the breaking of the stipulated weak-link, or to represent the limited torque output of an engine.

Generally, in the early part of the launch, CM will be the limit, and F will be less than FM. Towards the top of the launch, due to the different angles involved, F will reach FM for values of C less than CM. The programme is arranged so that neither limit is exceeded, but one is always effective.

Axes stationary with respect to the wind (i. e. drifting backwards with respect to the ground) have been taken. The co-ordinates of the glider are X, Y. In this reference frame, the winch has co-ordinate Z initial + UT, where U is the wind speed.

The "backwards" component B describes the wind drag and weight of the cable in so far as they affect the reaction at the glider.

The ground run, take off and early shallow climb are not included in the programme. Instead, appropriate initial values for the position of the glider at the start of the steep climb are inserted.

3. Logic sequence

Hor. distance glider to winch

$$H = Z - X$$

Straight-line distance glider to winch

$$R = \sqrt{H^2 + Y^2}$$

Component of C along R

$$S = \sqrt{(CM)^2 - B^2}$$

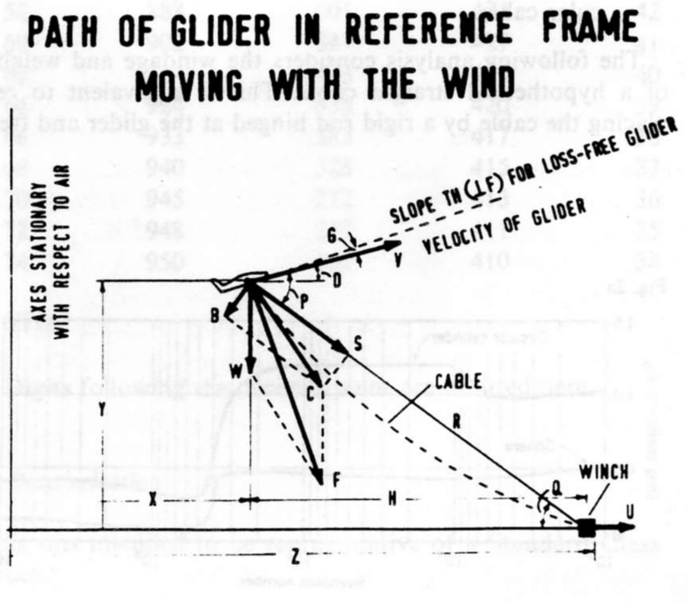
Applied force on glider $F = \sqrt{(S + WY/R)^2 + (B + WH/R)^2}$

If F exceeds FM, revise S as follows:

$$S \text{ (revised)} = \sqrt{FM^2 - (B + WH/R)^2} - WY/R$$

Cable tension $\qquad C = \sqrt{S^2 + B^2}$

Fig. 1



Slope of path for drag-free glider

$$TH = F_x/F_y$$

$$TH = \frac{SH/R - BY/R}{W + BH/R + SY/R}$$

$$TH = \frac{SH - BY}{WR + BH + SY}$$

Angle of flight-path to horizontal

$$D = \text{Arc tan}\,(TH) - G$$

Increments to co-ordinates

$$\triangle X = V \cos D \triangle T$$

$$\triangle Y = V \sin D \triangle T$$

$$\triangle Z = U \triangle T$$

4. *Wind and gravity forces on the cable*

The drag co-efficient for round wire varies with Reynolds Number as shown in Fig. 2a (from Ref: 1). The writer did not find equally comprehensive data for stranded cable. For Reynolds Numbers of the order 10^4 to 10^5 which are of interest in electric power lines, a drag co-efficient of 1.45 has been given, as compared with 1.2 for round wire. (Ref. 2). For a Reynolds Number of 8000, which corresponds to 4.1 mm diameter at 100 km/hr, Ref. 3 dating from 1917, gives a drag co-efficient of 1.2 for stranded cable.

For cable inclined to the wind direction Ref. 3 states "the tangential component is small, while the force perpendicular to the wire is roughly proportional, up to 70° inclination to the current, to the square of the velocity component normal to the wire". This is equivalent to findings elswhere (e.g. Ref. 4) that " the variation of drag with angle of incidence is roughly as $\sin^3 \alpha$."

The normal force per metre of cable is therefore equal to drag co-efficient x cable diameter x normal dynamic pressure

$$= C_D \; x \; d \; x \; av^2/2\,g$$

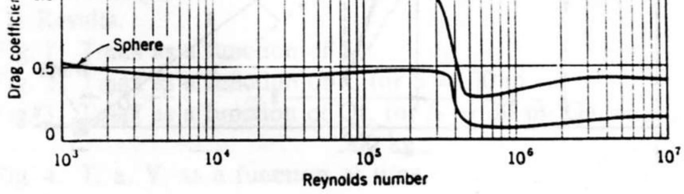
(where a is specific weight of air = 1.225 kg/m³ at 15° C v is normal wind velocity, m/s).

$$= \frac{C_D d}{16} v^2$$

$= AK1\,v^2$ where the constant AK1 describes a particular cable.

The following analysis considers the windage and weight of a hypothetical straight cable. This is equivalent to replacing the cable by a rigid rod hinged at the glider and free to bend at the winch. The error involved increases with the amount of bow as discussed in section 8.

Fig. 2a



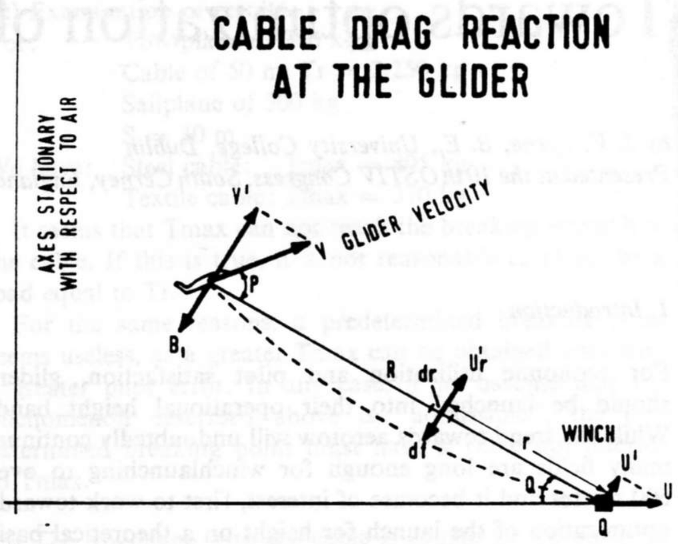


Fig. 2

In Fig. 2 the normal velocity U_r^1 is used to compute the drag on the elementary length dr. Moments are then summed about the winch position Q:

The transverse velocities of the cable at the ends are

$V^1 = V \sin P$. (designated S^1 in the programme).

$U^1 = U \sin Q$

hence $\quad U^1_r = U^1 + \frac{r}{R}(V^1 - U^1)$

drag $\quad df = (AK1)\,(U^1_r)^2\,dr$

moment $\quad dm = r\,df = (AK1)\,r\,(U^1_r)^2\,dr$

$$dm = (AK1)\,r\left[(U^1)^2 + \frac{r^2}{R^2}(V^1 - U^1)^2 + 2\frac{r}{R}U^1(V^1 - U^1)\right]dr$$

Hence, the wind drag reaction at the glider

$$B_1 = \frac{1}{R}\int_0^R dm$$

$$B_1 = (AK1)R\left[\tfrac{1}{4}(V^1)^2 + \tfrac{1}{6}V^1U^1 + \tfrac{1}{12}(U^1)^2\right]$$

From Fig. 3 the cable weight reaction

$B_2 = \frac{1}{2}(AK2)\,H$

where AK2 is the weight per metre of the cable.

The total reaction $B = B_1 + B_2$ is evaluated in line 24 of the computer programme, and is included in the print-out.

It is interesting to note that at 100 km/hr (27.8 m/sec) the wind loading on 4.1 mm stranded cable is $AK1\,(v)^2$

$= .000308 \times (27.8)^2$

$= 0.24$ kg/m or 3.6 times the gravity loading.

While the full value of this transverse velocity will only affect the glider end of the cable near the top of the launch, it is nevertheless true that wind forces are predominant in causing bow.

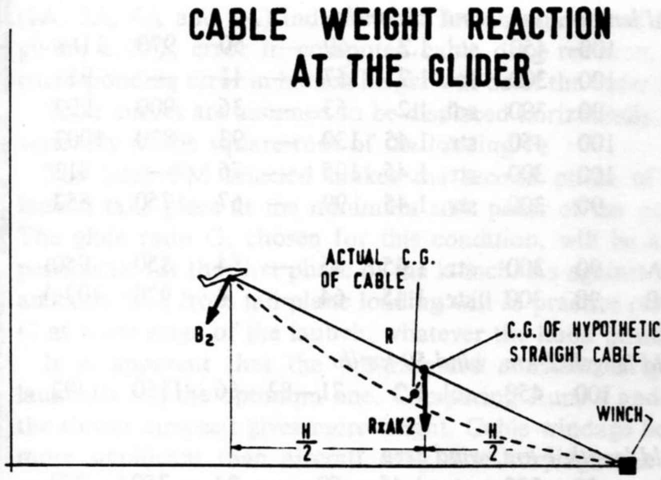


Fig. 3

5. The Computer programme, written in "Load and go" Fortran for IBM 1620 digital Computer

```
ACCEPT, X, YN, T, W, G
ACCEPT, Z, B, DELT, V, CM
ACCEPT, FM, AKI, AK2, U, TIM
ACCEPT, DTIM
25 TIM=TIM+DTIM
21 Y=YN
H=Z—X
R=SQR(H*H+Y*Y)
S=SQR(CM*CM—B*B)
F=SQR[(S+W*Y/R)*(S+W*Y/R)+(B+W*H/R)*
  (B+W*H/R)]
IF (F—FM) 11, 11, 12
12 S=SQR[FM*FM—(B+W*H/R)*(B+W*H/R)]
  —W*Y/R
11 C=SQR(S*S+B*B)
TOM=TIM—DTIM
IF (T—TOM) 13, 14, 13
14 PRINT, T, Y, H, C, B
13 TH=(S*H—B*Y)/(W*R+B*H+S*Y)
D=ATN(TH)—G
P=D+ATN(Y/H)
X=X+V*COS(D)*DELT
YN=Y+V*SIN(D)*DELT
Z=Z+U*DELT
SI=V*SIN(P)
B=.5*AK2*H+AK1*R*[.25*SI*SI+SI*U*Y/(R*6.)
  +U*U*Y*Y/(R*R*12.)]
IF (YN—Y) 31, 32, 32
32 T=T+DELT
IF (T—TIM) 21, 25, 25
31 STOP
END.
```

* denotes multiplication; SQR = square root of; T and DELT = time and increment of time for computing; TIM and DTIM = time and increment of time for print-out; YN = new value of Y; ATN = arc tan.

Numerical data and initial values are inserted according to the four ACCEPT instructions. This and the ensuing print-out are shown in full for Run 1. All values are in metre kilogram second units.

Run. 1

```
0. 0. 0. 300. .0357
1920. 70. .5 27.8 450.
710. .0001755 .0336 0. 0.
2.

T       Y       H       C       B
0       0    1920     450      70
2      41    1882     450      67
4      82    1845     450      67
6     122    1806     450      66
8     162    1767     450      65
10    201    1728     450      64
12    239    1688     450      63
14    277    1647     450      63
16    315    1606     450      62
18    351    1564     450      61
20    387    1522     450      60
22    422    1479     450      59
24    457    1435     450      58
26    490    1391     450      57
28    523    1346     450      57
30    555    1300     450      56
32    586    1254     450      55
34    616    1207     450      54
36    645    1160     450      53
38    673    1112     450      52
40    700    1063     450      51
42    726    1014     450      50
44    751     964     450      49
46    775     914     450      48
48    797     863     450      47
50    818     812     450      46
52    838     760     445      45
54    856     707     440      44
56    873     654     435      43
58    888     601     431      42
60    902     547     427      41
62    914     493     423      40
64    924     438     420      39
66    933     383     417      38
68    940     328     415      37
70    945     272     413      36
72    948     217     411      35
74    950     161     410      34

STOP
```

Digits following the decimal point are omitted here.

6. Data selection

This was intended to be representative of a Standard Class glider.

All-up weight $W = 300$ kg
Permitted weak-link $= 600$ kg
Permitted launching speed $V = 27.8$ m/s (100 km/hr)
90% permitted speed $V = 25$ m/s (90 km/hr)
Speed for min. sink (free flight)
$= 65$ km/hr
For $V = 100$ km/hr $FM = 300 \times (100/65)^2 = 710$ kg
For $V = 90$ km/hr $FM = 300 \times (90/65)^2 = 575$ kg
Gliding angle at min. sink $G = {}^1/_{28} = 0.0357$ radians.

The fact that G will be better than this for loadings less than FM is neglected. The cable force is assumed to pass through the C. G.

It is not realistic to consider cable tensions approaching the weaklink breaking load. A value 75% of this (CM = 450 kg) has been arbitrarily chosen, and for comparison a lower value of 300 kg, which can represent an easier launch, an inadequate winch or the restriction imposed by a weak-link of less than 600 kg.

Two cables are compared. The 4.1 mm stranded is a typical winch cable. The 2.34 mm solid wire has been used for several years with the automobile-pulley system and is perhaps the lightest wire that can be considered. The Reynolds Numbers at 100 km/hr are respectively 7800 and 4400. The corresponding drag co-efficients are 1.2 (with some doubt) and 1.0 (see Section 4). The constant AK 1 therefore has the values

AK 1 = 0.000308 kg/m at 1 m/s for 4.1 mm stranded cable.
AK 1 = 0.000146 kg/m at 1 m/s for 2.34 mm solid wire.

Runs 1A, 3A, 4A and 6A used these values. For all other runs, values 20% higher were taken. The cable weights are

AK 2 = 0.066 kg/m for 4.1 mm stranded cable.
AK 2 = 0.0336 kg/m for 2.34 mm solid wire.

The take-off phase has been allowed for by deducting from the gross field lengths of 1 and 2 km the distance covered in accelerating at 0.5 g to an airspeed of 100 km/hr. The initial value of the cable windage and weight reaction B is estimated.

7. *Summary of computed results*

Run	Speed km/hr	CM kg	Cable type C_D	B kg	Height (m) Transition	Height (m) Final
Field length 2 km, wind zero						
1	100	450	sol. 1.2	67 — 34	830	950
2	100	300	sol. 1.2	55 — 29	—	777
3	90	300	sol. 1.2	52 — 24	720	787
4	100	450	str. 1.45	127 — 67	720	845
5	100	300	str. 1.45	103 — 54	—	684
6	90	300	str. 1.45	96 — 46	640	699
1A	100	450	sol. 1.0	62 — 30	830	963
3A	90	300	sol. 1.0	48 — 20	730	796
4A	100	450	str. 1.2	117 — 56	730	866
6A	90	300	str. 1.2	91 — 40	650	713
Field length 2 km, wind 25 km/hr						
8	100	450	sol. 1.2	69 — 50	970	1168
9	100	300	sol. 1.2	57 — 41	—	953
10	90	300	sol. 1.2	53 — 36	900	992
11	100	450	str. 1.45	130 — 93	820	1007
12	100	300	str. 1.45	105 — 76	—	813
13	90	300	str. 1.45	99 — 67	750	852
(13A	90	300	str. 1.45	45 — 64	850	950)
(13B	90	300	str. 1.45	64 — 4	920	1036)
Field length 2 km, wind 50 km/hr						
14	100	450	sol. 1.2	71—82—66	1150	1492
Field length 1 km, wind zero						
7	90	300	str. 1.45	50 — 24	350	379
15	100	450	str. 1.45	66 — 35	400	458

CM cable tension limit.
B the two figures show the range of the cable weight and windage reaction during the launch.

The transition height divides the constant tension (= CM) and constant loading (= FM) phases. Where transition occurs, the final cable tension is FM — W.

Runs 13A and 13B are repeats of Run 13 but with cable weight and drag respectively neglected. It is seen that cable drag is about 1.8 times more significant than weight.

Eight of the flight-paths are shown in Figs. 4 and 5. The effect of wire size is seen to be greater for the higher launches of Fig. 5, relating to 25 km/hr wind. Comparing Runs 10 and 11, the solid wire at a tension of 300 kg gives almost the same height as the stranded cable at 450 kg.

The maximum winding power is the product of cable tension CM and the initial winding rate $\triangle H/\triangle T$, which for Run 1 is 18.6 m/s, giving 82 kW. A higher winding speed. say 25 m/s, is needed before the climb begins, and if a flat torque curve and fixed gear ratio are presumed, the actual engine capability will be 111 kW or 150 BHP, making no allowance for transmission losses.

8. *Discussion of assumptions in the programme*

The relieving effect of the ground on the cable is neglected. Early values of B are therefore pessimistic.

Ignoring of bow in computing the cable centre of gravity leads to optimistic values for B, and may be significant for long heavy cables. AT = 50 seconds for Run 1, the error was found to be 1%.

The wind drag on the actual bowed cable will differ from that on the hypothetical straight wire, except near the middle where the inclination is the same. Near the glider end the increase is maximum, corresponding to the cable having an extra inclination of $\sin^{-1} B/C$, the angle of sag. If it is assumed that the correction required varies linearly along the wire and is zero at the centre, it is found that the cable drag reaction at the glider is increased by 0.6 times the fractional increase in wind drag/unit length at the glider end of the cable. For Runs 1, 4 and 6 this works out at 6.5%, 14.5% and 24.5% half way through the launch.

A fixed correction of 20% was inadvertently introduced by the selection for Runs 1 to 15 of drag co-efficients 20% too high. The four Runs repeated without the correction

(1A, 3A, 4A and 6A) indicate that for an amount of bow giving a 20% error in computed cable drag reaction, the corresponding error in launch height will be of the order 2%.

Polar curves are assumed to be displaced horizontally and vertically as the square-root of the loading F.

The limit FM selected makes the second phase of the launch take place at the minimum sink point of the polar. The glide ratio G, chosen for this condition, will be a bit pessimistic for the first phase of the launch. As against this, an extra drag from tail plane loading will in practice reduce G at some stage of the launch, whatever the hook position.

It is apparent that the programmed constant airspeed launch is not the optimum one. Comparing Runs 9 and 10, the slower airspeed gives more height. Cable windage being more significant than aircraft drag, and varying with the square of the speed, it would seem that the glider should be flown quite near the stall throughout the launch. Furthermore, while operation at highest permissable cable and wing loadings gives the steepest path relative to the air, and the best height in zero wind, the criterion for optimization is more generally the path steepness in stationary axes. A more ambitious computer programme would select airspeed and cable load to give maximum ratio $\triangle Y/\triangle H$.

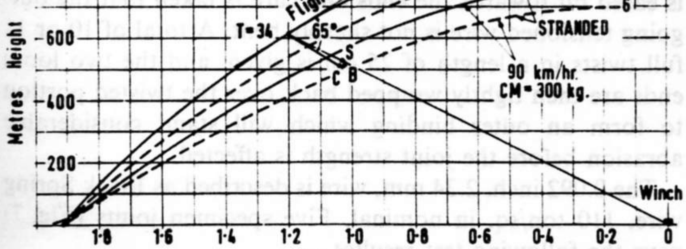
9. *Hook position*

The tailplane loading due to the moment of the cable force C about the centre of gravity reduces the glider efficiency and may impose a further restriction on the cable tension which can be supported. (Refs. 5 and 6). Hooks placed far forward increase both the cable bow and aircraft drag in the second half of the launch, so that the computed flight paths will not be attainable.

Several makers were kind enough to offer an opinion here. Rudolf Kaiser wrote: "The hook position is not selected to give feel of cable tension. It is so placed that no correction by elevator is necessary, to give maximum efficiency on winch tow. I think zero elevator pressure should be in the middle of the launch. But often the position of the hook depends on the arrangement of seat etc. within certain limits. An angle of about 60° against longitudinal axis should give a normal position."

Nicholas Goodhart (6) concludes: "The protection afforded by high stick loads in the launch is entirely illusory if not actually negative and hooks should be sited to give low moments."

Fig. 4



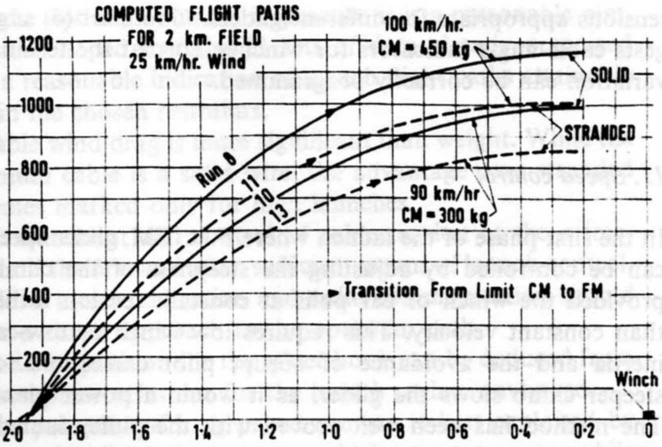


Fig. 5

Minimum tailplane losses would call for the time-average value of the elevator correction to be zero. On this basis the cable force vector should pass through the C. G. when the glider is half way along the launch path. For Run 1 (see Fig. 4), the angle between the cable pull C and the flight path is 65° at this point. For Run 6 at the lighter tension CM = 300 kg, the angle is 60°.

If to this angle of 60° = 65° is added the angle between the flight path and the longitudinal axis at the appropriate loading, the hook position is defined.

10. *Tension measurement and control*

Ideally, the winch or car should be an inertia-less device applying a programmed tension to the wire, and the extent to which this is achieved will determine both efficiency and the ability to absorb gusts without excessive surges in tension. Inherent tension limitation is given by the flat torque/speed characteristic of some winch engines, and the required fall in tension as the launch proceeds is to some extent given by the increasing winding radius.

In general however, direct tension measurement is desirable. Experience at Dublin with both hydraulic and mechanically actuated tensiometers for towcars suggests that to be useful they must be effectively damped against vibration, a time constant of about 1 second being suitable. Few winch designs lend themselves to easy addition of tension measurement gear. Where there is a final drive to a truck type rear axle, it may be feasible to use the torque reaction and neglect the error due to changing drum diameter. Another possibility is the addition of a tension-sensing pulley.

Quite apart from the optimization question, un-instrumented winches require great driving skill and it is suggested that new winch designs take account of the need for tension measurement.

At the winch, cable tension will vary over a wider range than it does at the glider, because of cable weight. For the pulley launch at Dublin, tension is reduced by rule of thumb, using coloured sectors on the gauge to indicate the range of tensions appropriate for different gliders. Goodhart (6) suggests cable angle indicators for winches, so that the tension variation can be correctly programmed.

11. Speed control

In the first phase of the launch where $F < FM$, glider speed can be controlled by adjusting the steepness of the climb, provided the winch or car pulls at constant tension rather than constant velocity. This requires low winch or tow-car inertia and the avoidance of abrupt pilot corrections. A steeper climb slows the glider, as it would a power plane. The method has been well proved with the pulley launch, where in general the driver has a bad view of the glider and must launch "blind".

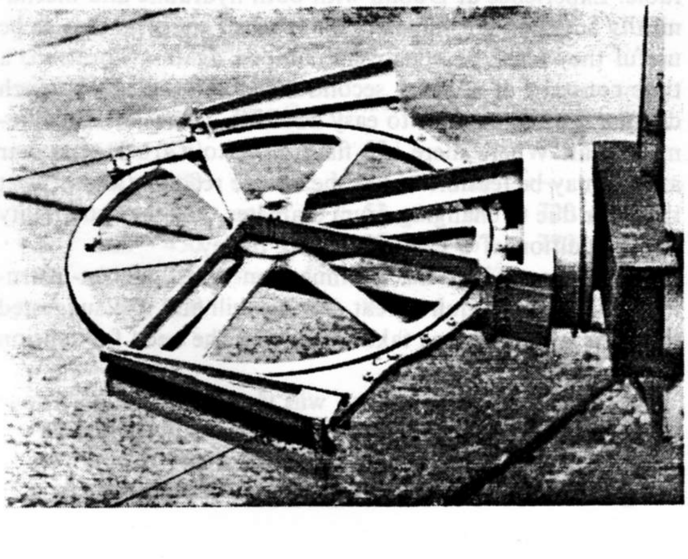
Excess tension in the second phase of the launch will cause overspeed or stalling, depending on hook position. Radio communication from pilot to winch offers the best prospect of satisfactory control at high loadings. It is doubtful if pilots can sense the onset of stall (mushing) on the launch, and there appears to be a need for an angle of attack indicator if minimum sink conditions are to be realised.

12. The pulley launch

Conventional automobile tow gives a more downward pull at the glider than does a winch and the optimum cable length varies with wind strength. Long cables are difficult to handle after release. By bringing the cable round a pulley (Fig. 6) situated where the winch would normally be, a winch-type launch is given. At the end of each launch the car arrives with the cable at the launching area. The cable has the full field length, alternate ends are used, and there is no separate operation of cable retrieving.

Details of the system at Dublin have been described elsewhere (6). It has now been in continuous use for two years and more than 4000 launches have been made. From runways of 1.8 km, 600 m is reached by 300 kg gliders in zero wind using tensions which do not exceed 300 kg. 900 m is reached in strong winds without any cable handling difficulties. With 4 or 5 aircraft one car has been adequate, since many of these launches result in soaring. The launch rate could be increased to an estimated 20 per hour by using two cars.

Fig. 6



Emphasis to date has been on general workability by club members rather than optimization. The existing tow-car, a Fordmatic V8 stripped down to reduce inertia, is underpowered and it is clear that engines of over 200 BHP would be needed to give a draw-bar pull of 450 kg over the speed range.

The pulley has a diameter of 2 feet (60 cm) chosen to avoid fatiguing the solid wire. It is so mounted that, provided one wire is directed along the runway the other has complete angular freedom. Arrangements using two pulleys are also possible and perhaps preferable. The design of the guides is critical and must positively prevent the cable from jumping the groove. Inadvertent glider release under tension sends a vicious travelling wave of looseness down the wire which would foul up any winch and yet will pass harmlessly through a properly guarded pulley.

Parachutes about 0.9 m square are used to prevent kinking of the wire after release by the glider. Tension is kept on the wire at all times, and breaks due to kinking are less frequent than with conventional car-tow.

The essential auxiliaries have proved to be a radio link from launch point to tow-car and a good cable storage system. Initially there was a problem of persuading the sceptical to operate the necessary control techniques. A very good reliability is now achieved with fewer people and less skill than for normal winch driving.

13. Cable

Optimization for height requires the lightest, thinnest, smoothest cable having a strength margin over the permitted weak-link. This will be a solid steel "spring" wire.

In practice, stranded wires are demanded by many winch designs and methods of operation, and the cable size itself is determined by wear and work-hardening considerations as well as the need for joints in part-worn cable to be stronger than the weak-link. Spliced joints can approach the basic wire strength. Winch fairleads and drums should have sufficient diameter to avoid fatiguing the cable. Several existing designs have adequate fairlead pulleys of about 25 cm dia.

Solid wire techniques developed for the automobile-pulley system may be of interest for winch use also. Minimum bending radius is 30 cm. Joints (Fig. 7) have 90% of the basic wire strength, good flexibility, good resistance to abrasion against runways, and do not develop loose tails. As in a splice, the tension is gradually transferred from one wire to the other throughout the length. For this reason, the high rate of twisting of about 6 full twists in the central 12 cm is eased off towards the ends and care is taken that the outgoing tensioned wire is not sharply bent. A total of 10 or 11 full twists in a length of 25 cm is given, and the two loose ends are then tightly wrapped back over the twisted portion to form an outer binding which will stand considerable abrasion before the joint strength is affected.

The 0.092 inch, 2.34 mm, wire is described as Black Spring wire, 110 ton/sq. in nominal. Five specimen joints (Fig. 7) gave the following test results:

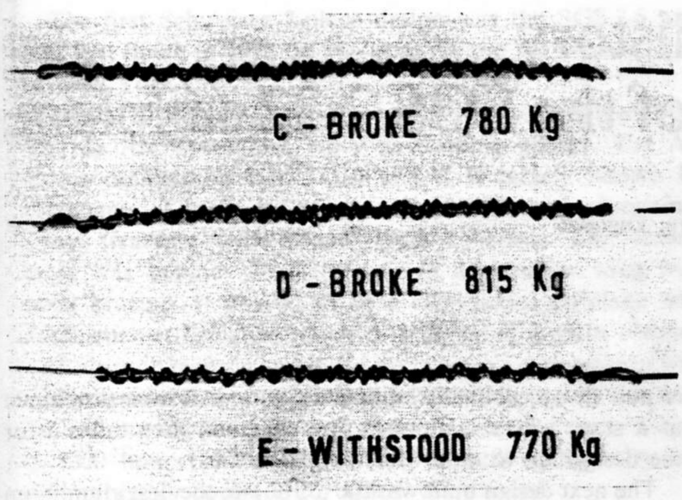


Fig. 7

Length	Twists		Wraps	Broke	
cm	Tight	Total		lb.	kg
23	5	10	31	1740	790
28	6	10	36	1770	800
25	7	11	29	1720	780
25	6	11	34	1800	815
23	6	11	27	>1700	>770

Basic wire — straight sample	1860	840
Reef knot	1140	515
Reef knot	1160	525

Other grades of wire tested required fewer twists to develop 90% joint strength. Proving tests are recommended, to establish the optimum configuration for a particular wire type.

14. Conclusions

The simple programme for the constant air-speed launch is shown in full so that readers with access to a computer may insert their own data. While constant speed does not give the optimum launch, in practice it is a reasonable aim, and it is hoped that the 21 sets of data already processed give a reasonable indication of launch flight paths attainable within the chosen restraints.

Cable wind drag is more significant than weight. While the optimum cable is a solid wire, the advantage over stranded becomes marked only for high launches.

Measurement and control of cable tension at the prime-mover is the first and often sufficient means of launch control. Angle of attack indication and radio communication should allow a closer approach to the optimum path.

The best position for the glider hook can be deduced from the computer print-out for the launch regime envisaged.

The potential of long paved runway is best exploited by the automobile pulley system, which converts automobile tow into what is effectively a winch launch.

15. References

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