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A radically new, ultra-high-speed method for the installation of cables in ducts

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Abstract

A radically new, ultra-high-speed method for the installation of cables in ducts is described. A high-speed moving cable will slide on it's own, equally distributed, inertia without suffering exponential force build-up in curves. Centrifugal forces are compensated for any curvature of the duct by a proper cable tension. Some ways to supply this tension and to accelerate the cable before installation are described. Theory says that 10 km of fibre-optic or other cable can be installed in one shot of 2 minutes. This theory is checked by scale-model straight- and looped-trajectory field trials. Here 1536 m of cable is installed in 2 minutes and 5 right-angled curves and 6 loops are passed in 7 seconds respectively. For understanding, friction coefficients between cable and duct are measured at high speeds.

Introduction

The use of fibre-optic cables for telecommunication has caused an enormous increase in practical cable lengths. This is caused by the lower cable weight which allows for larger lengths on one single reel. In addition, as the attenuation of the fibre itself is very low, splices are the dominant loss contributors and should be avoided as much as possible. In the past short pieces of telecommunication cable were buried directly into the ground. Nowadays in many countries fibre-optic cables are installed in pre-installed ducts. A commonly used technique for installing cables in ducts is pulling with a winch rope. When the cable is under tension, the cable will be pulled against the duct-wall in curves and undulations in the trajectory, causing friction. The pulling force will then increase exponentially with length due to the fact that the friction is proportional to the tension in the cable[1]. This so called "capstan effect" limits the cable length that can be installed in one single pull. The "capstan effect" can be avoided by distributing the pulling force along the length of the cable. Cable blowing is a well-known technique to achieve this.[2,3]

In this paper a radically new approach, the "high-speed technique", is presented where the pulling force is also distributed along the length of the cable.[4] First the cable and the reel are accelerated to a very high (rotational) speed. Some ways to perform this are described. The cable then decelerates until standstill, sliding in the duct, driven by its own inertia. The inertia "force" is equally distributed over the length of the cable. Due to high (apparent) centrifugal forces that appear in curves the deceleration will be high and the cable stops soon. These centrifugal forces can be compensated by applying a proper tensile force to the cable. In that case the compensation holds for any curve, no matter what its radius of curvature is. The tensile force in the cable is obtained by applying a high enough force at the cable head, by means of a winch rope or a shuttle. The feeding of the cable is controlled such that the transversal force at the cable, measured in a curve at the injection side, is kept zero.

In a field trial a lightweight cable, stored in "figure-eight's", is installed in a duct with the use of an air-powered shuttle. The experimental setup is kept simple, avoiding high power engines, as it is not meant to reach maximum performance, but to check the theory. This experiment is performed to prove the theory for the "sliding inertia". In another experiment 100 m of cable, stored on a reel now, is installed in a duct in which 5 right-angled curves and 6 complete loops are present. This experiment is performed to prove theory for the centrifugal-force compensation by means of a proper cable tension. For better understanding also measurements of the friction coefficient between cable and duct are performed at high speeds (appendix).

Theory

The theory of force build-up in cables which are pulled in ducts is developed long ago.[1] In this theory reaction forces exercised by the duct on the cable in different directions due to the cable mass and due to the cable tension in curves are taken into account. Forces due to a change in speed (acceleration) of the cable are low in conventional installation (speed of order 1 m/s) and are hence not considered in the above mentioned (static) theory. This is also true for the centripetal reaction forces of the duct, necessary to lead the cable through curves. In the present paper an installation technique is described in which the speeds are ultra-high (order 100 m/s). This means that the installation of the cable must be treated dynamically, taking into account all above mentioned terms.

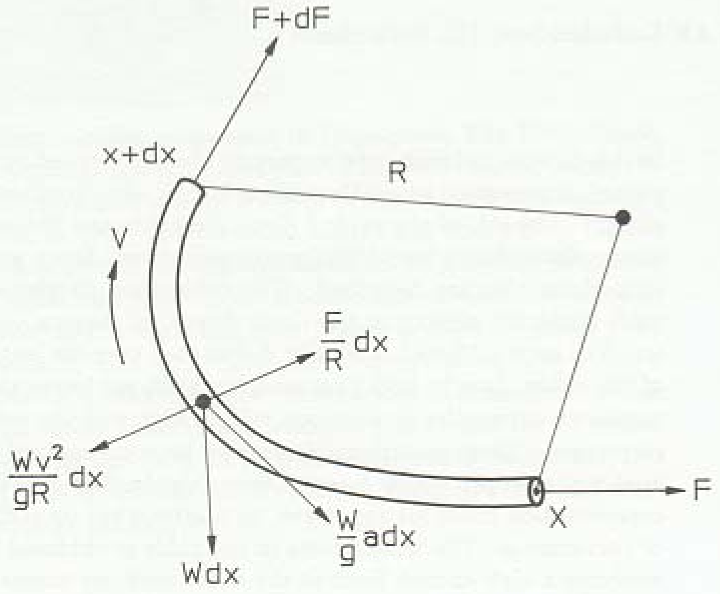

Figure 1: Forces acting on a cable moving in a duct

In figure 1 all forces acting on a piece of cable dx, moving with a uniform (longitudinal) speed v, are shown. For reasons of clarity not the reaction forces of the duct on the cable, but the (apparent) forces of the cable itself are given. Forces due to cable stiffness and buckling or to slopes in the ducts can also be treated, but are not considered in this paper.[3,5] The duct reacts with a normal force which compensates the resultant of the gravity force Wdx, the centrifugal force $Wv^2dx/(gR)$ and the transversal component of the cable tension Fdx/R, with W the cable-weight per unit of length, g the acceleration of gravity, v the speed of the cable and R the radius of curvature of the duct. The friction force acting on the cable follows by multiplying this normal force with the friction coefficient f between cable and duct. The increase dF of a pulling force F over a length dx for this dynamic situation is obtained by adding the "inertia force" $Wadx/g$ of the cable, with a for the acceleration of the cable, to the mentioned friction force:

$$dF = \left[\frac{W}{g}a + \frac{f}{R}\sqrt{(WR)^2 + (F - Wv^2/g)^2}\right] dx \qquad (1)$$

In this formula it is assumed that the curve in the duct is in a horizontal plane. In practice ducts can be curved in all directions, but this does not change the force build-up very much.[3] For zero a and v the basic formula for the static force build-up is obtained.[1]

Consider the situation that $a = -fg$ and $F = Wv^2/g$. From equation 1 hence follows that $dF = 0$ which means that there is no force build-up in the cable anymore. The first condition means that the cable just slides by it's own inertia. The second condition means that a proper tensile force is applied to the cable in order to compensate for the centrifugal force of the moving cable. Both centrifugal force and transversal component of the cable tension are inversely proportional to R, which means that these effects compensate each other for every curvature once the compensation criterion is reached. In this case every curve can be followed by a high-speed moving cable without transversal forces acting on the cable which disturb the curve.

Interlude: An example in which nature itself controls the proper tensile force, to compensate for the centrifugal force, is a high-speed running piece of cable in a closed loop (figure 2). In that case every shape of the cycling cable can be obtained. In figure 2 an artificially applied perturbation is shown, which is maintained for a relatively long time (> 100 cycles), in a cable that runs with 50 m/s. This may be an unexpected result since one expects a nice round loop as is the case with a lasso. The difference can be explained by the fact that the "knot" connecting the rope, held by the cowboy, with the loop is "resetting" the path every turn. It is now clear that a moving cable under proper tension can pass a stationary perturbation without transversal forces acting on that cable to disturb the perturbation. This can be compared with a tensed, stationary, string in which a perturbation travels with speed $v = \sqrt{FW/g}$, set by nature, which is the same relation between speed and tension.[8] Another example, in which nature controls the proper tension, is a rope following a launched harpoon which is accelerated from a resting pile (this is not true when using a reel to store the rope).

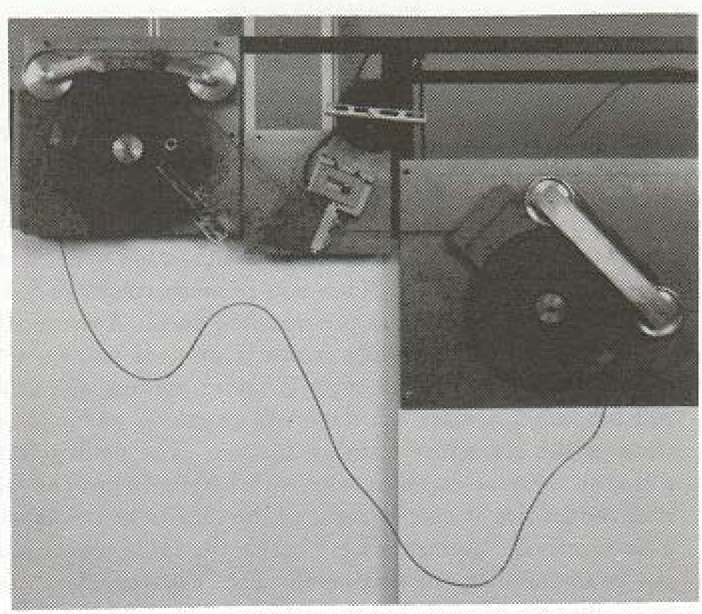

Figure 2: High-speed (50 m/s) running loop of cable with artificially applied perturbation

When the above mentioned criteria of sliding and zero transverse force are fulfilled a situation is obtained in which a cable slides in the duct, decelerating, while the force along the cable remains constant. The length ℓ over which the cable slides in this condition is obtained with $a = -fg$ and by using the boundary condition that the speed of the cable drops from v_0 at the start to zero at the end:

$$\ell = \frac{1}{2}\frac{v_0^2}{fg} \qquad (2)$$

When the transversal component of the cable tension does not exactly compensate the centrifugal force of the moving cable, $dF = 0$ is obtained from equation 1 when $a = -fg \cdot \sqrt{1 + (F_0/WR)^2}$ with $F_0 = F - Wv^2/g$. In this case a more general formula for the sliding installation length is found:

$$\ell = \frac{1}{2}\frac{v_0^2}{fg} / \sqrt{1 + (F_0/WR)^2} \qquad (3)$$

The force F_0 is the effective cable tension which is measured indirectly by measuring the transversal force of a cable moving through a curve. In figure 3 an experimental setup is shown which is used to measure F_0 at the injection side of the duct. The measured transversal force F_t is equal to $2\sin(\alpha/2) \cdot F_0$.

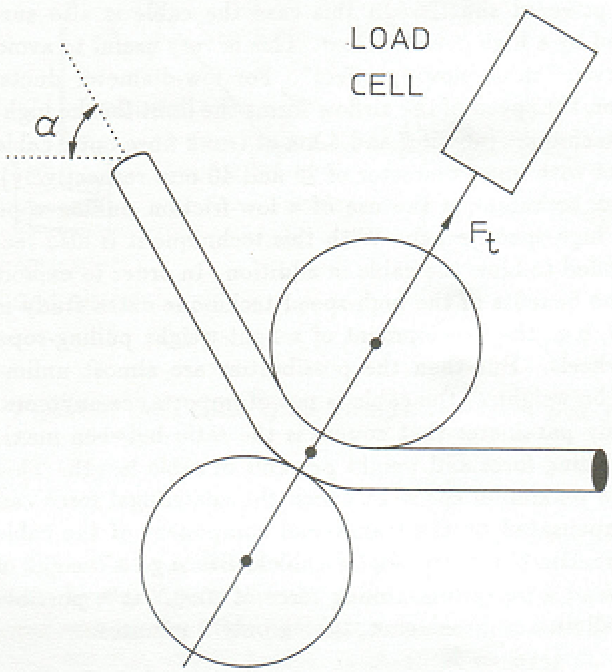

Figure 3: Experimental setup for measuring effective cable tension F_0

When the deceleration of the cable is controlled by keeping the effective cable tension F_0 at the injection side of the duct as small as possible, and when the applied force at the cable-head is equal to Wv^2/g (plus the mentioned small F_0) the cable slides over a length ℓ, according to formula 3. When the pulling force at the cable head is much higher than Wv^2/g the cable tension decreases to the latter value along the cable from the head until the injection side. In this case the deceleration of the cable is less than in the situation that F_0 is kept small all along the cable. The heat production, caused by the friction between cable and duct, will however be larger. Care should be taken that this heat production is not too high. For this reason it may be necessary to control the pulling force at the cable-head too in cases of extremely high installation speeds (the heat-production per unit of time and length can be reduced down to fWv, which is left due to the cable mass). When the pulling force at the cable head is much lower than Wv^2/g the cable decelerates soon until the situation $F = Wv^2/g$ is reached at the cable head. When the pulling force at the cable head is zero, e.g. when the cable reaches the end of the duct, the cable stops soon.

A general solution of equation 1 may be obtained by substituting:

$$z = \frac{F_0}{WR} \qquad c = \frac{a}{fg} \qquad u = \frac{\sqrt{1+z^2} - 1}{z} \qquad (4)$$

After integration the next equation is obtained:

$$\frac{f}{R}x = \left[\text{arcsinh} z - \frac{2c}{\sqrt{1-c^2}}\arctan\left[\frac{(1-c)u}{\sqrt{1-c^2}}\right]\right]_{z=z_0}^{z=z} \qquad (5)$$

Note that for a and v equal to zero and with $x = R\theta$, with θ the angle along which the duct is curved, again the force build-up formula in curves for the static situation is obtained. Equation 5 holds for $c < 1$. The second part of the right-hand side of equation 5 is equal to u when $c = 1$ and goes to infinity for $c = -1$. For $c > 1$ equation 5 can be re-written by using $i \cdot \arctan(ix) = -\text{arctanh}(x)$ with i defined as $\sqrt{-1}$.

It is assumed that the cable on the reel is accelerated until the maximum speed v_0 before the cable is installed (how will be discussed later). This means that the pulling force F on the cable is not able to accelerate cable and reel in the first part of the trajectory any further. The acceleration a will hence be equal to zero. This situation is maintained until an installation length x_0, which is obtained by solving equation 5 for $c = 0$:

$$x_0 = \frac{R}{f}\left[\text{arcsinh}\{\frac{F_0}{WR}\}\right]_{F_0=F_0(0)}^{F_0=F-Wv_0^2/g} \qquad (6)$$

Next the installed length, speed and acceleration of the cable can be obtained iteratively with equation 5. A numerical example, with $W = 1N/m$, $R = 30m$ (corresponding to undulations of $2^o/m$), $f = 0.15$ - this is lower than for traditional pulling because with the described technique the peaks in friction, occuring when the cable starts moving from standstill, do not appear -, $F = 2000N$ (cable-head) is given in figure 4.[3] The starting speed used is $v_0 = 100m/s$ and it is assumed that $F_0(0)$ is kept zero.

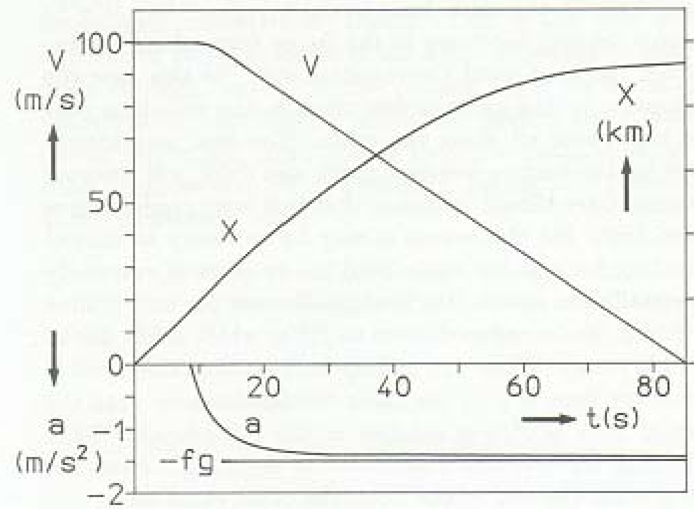

Figure 4: Numerical example of cable installed-length x, speed v and acceleration a as a function of time t

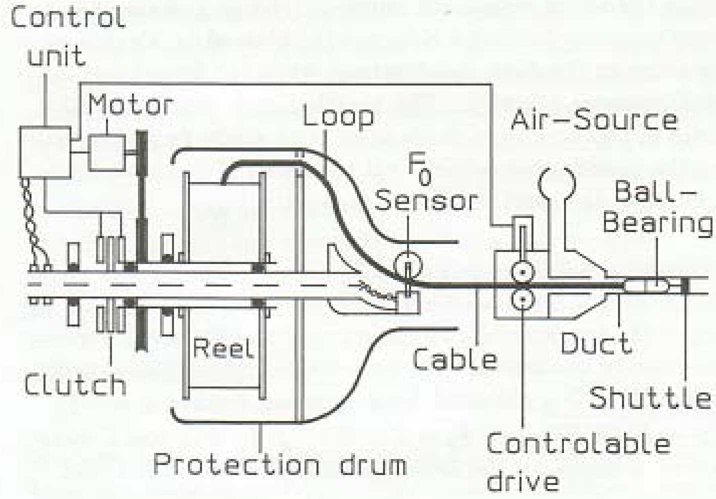

Figure 5: Mechanism to accelerate the reel before installation

Practice

Until now it was just assumed that cable installation started with a very high speed. This is not easy to achieve. A lot of energy is necessary to accelerate a long cable on a reel to a very high speed. If this energy must be applied in a very short time, a lot of power is needed. It is preferable to accelerate the complete cable reel first before starting the installation of the cable in the duct. The development of a mechanism that grips the cable from the high-speed running reel is one possibility. A more clever and safer method is shown in figure 5.[4] A cable is inserted in a duct first and attached to a pulling source (an air-powered shuttle in figure 5). The cable is however de-coupled from the pulling source for rotation about its axis. The reel, cable loop and controlling-, guiding- and protection-means will all together start with rotating until the desired speed is obtained. In that case the cable piece inside the duct will rotate around its axis. Then all rotating (light-weight) parts, except the cable reel, will be braked in a very short time. From that moment on the cable runs into the duct with very high speed while the rotation around its own axis has stopped. Now the sliding situation is reached in which the speed of the reel is controlled by the F_0-sensor.

Another possibility is to accelerate a cable reel in the first part of the installation very quickly. This can be performed by using high-power engines or by using energy stored in a flywheel in combination with a high-capacity clutch. It is also possible to avoid the need to accelerate the whole cable length in the first time. A cable can also be accelerated bit by bit, e.g. when the cable is stored in a heap or in "figure-eight's".

Another practical point is the pulling-source, necessary to supply the cable tension which is needed to compensate the effect of the centripetal force. One method is the use of an air-powered shuttle. In this case the cable is also surrounded by a high-speed airflow. This is very useful to avoid a reversed "cable-blowing effect". For low-diameter ducts, however, the speed of the airflow forms the limit for the high-speed technique (about 2 and 4 km of trunk fibre-optic cable in ducts with inner diameter of 26 and 40 mm respectively). Another technique is the use of a low-friction pulling rope with a high-speed winch. With this technique it is also recommended to blow the cable in addition. In order to exploit fully the benefits of the high-speed technique extra study is needed, e.g. the development of a light-weight pulling-rope with wheels. But then the possibilities are almost unlimited. The weight of the cable is not of importance anymore. The only parameter that counts is the ratio between maximum pulling force and weight per unit of cable-length. This sets the maximum speed at which the centrifugal force can be compensated by the transversal component of the cable tension. For trunk fibre-optic cables with e.g. a weight of $1N/m$ and a maximum pulling force of $2000N$ it is possible to install 10 km in one shot, taking only 2 minutes.

Experiments

Straight trajectory

Most of the experimental setups which are described in the preceding chapter need powerful or difficult to develop equipment. For this reason a simple scale model is build in order to prove the theory. The experiments are performed with light-weight ($W = 0.12N/m$, $\Phi = 3mm$) PVC-jacketed single-fibre cables. To accelerate a reel with a few kilometers of this cable in a very short time would still need a lot of power. For this reason the cable is stored in "figure-eights" in a special container as is shown in figure 6. An air-powered shuttle is used to supply the pulling force. In order to eliminate for a pressure build-up in front of the shuttle this space is evacuated before the start. A device as is shown in figure 3 is used to measure the effective cable tension F_0 just before entering the pressurized space. The speed of the pick-up wheel is controlled in such a way that F_0 is maintained as small as possible. The effect of the pressure rise when the cable enters the duct is overcome by forcing an airflow with high speed through a narrow tube first and bleeding a part of this flow after this tube. The experiment is performed in a rather straight (one 270°-curve) trajectory of 2 km of HDPE ducts with an inner diameter of 26 mm. Only a very small amount of paraffin oil is present in the duct for lubrication.

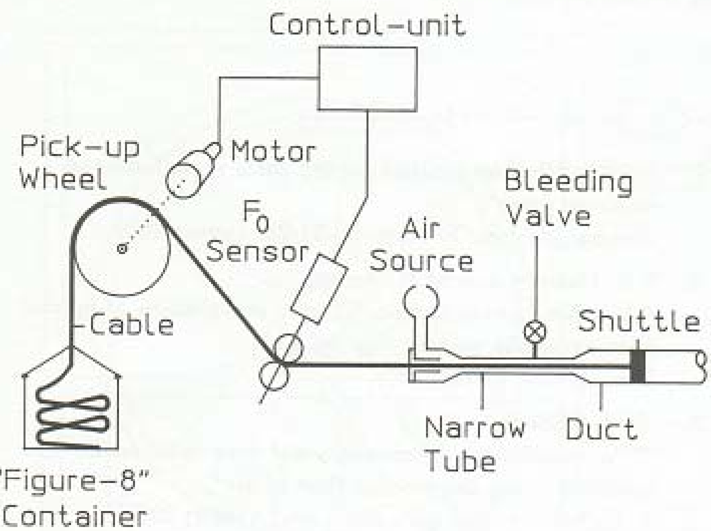

Figure 6: Schematic of the straight-trajectory field trial

In figure 7 the speed of the cable is given as a function of time. In this figure also the transversal force F_t, which is a measure for the effective cable-tension F_0 is shown. After about 60 s F_t shows a peak (pick-up of an irregular loop) resulting in a sudden decrease in speed. The speed however recovers afterwards. Maybe this indicates that the pulling force is still effective here. This is possible because the trajectory is rather straight. The decrease of speed in the first part of the trajectory can be explained by a higher friction coefficient between cable and duct at high speeds as may be expected for lubricated ducts (see appendix). Finally a length of 1536 m was installed in only 2 minutes with a maximum speed of 34 m/s. It was quite impossible to install this length by normal pulling and hence the "sliding on inertia" effect is proved by this experiment.

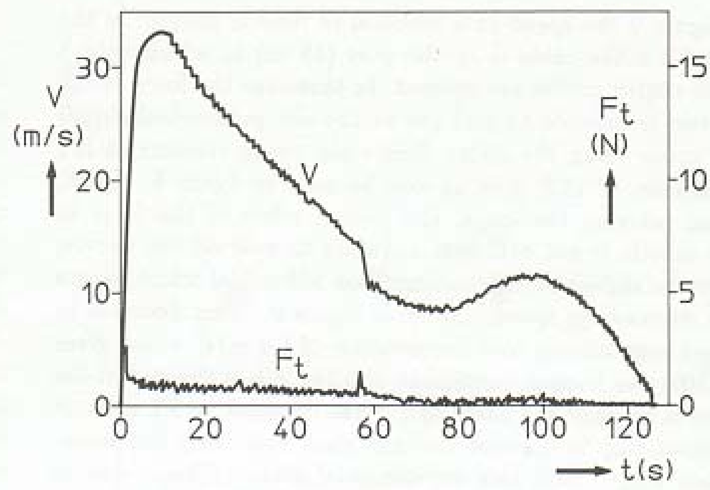

Figure 7: Speed v and effective cable tension F_0 as a function of time t in the straight-trajectory field trial

Looped trajectory

The effect of compensating the centrifugal-force by a proper cable tension is proved in a shorter (85 m) trajectory in which 5 right-angled curves and 6 loops of 360° (last 40 m) are present. Now a special "dry- lubricated" HDPE duct with an inner diameter of 12 mm is used. The shorter cable length gives the possibility to install from a cable reel, which is driven by a controlled motor to give a small effective cable-tension F_0. Because this trajectory is extremely curved the effective cable-tension F_0 inside the duct must be kept very small (formula 3). Therefore another "sensor/drive" unit (no. 2) is placed inside the pressurized space as can be seen in figure 8.

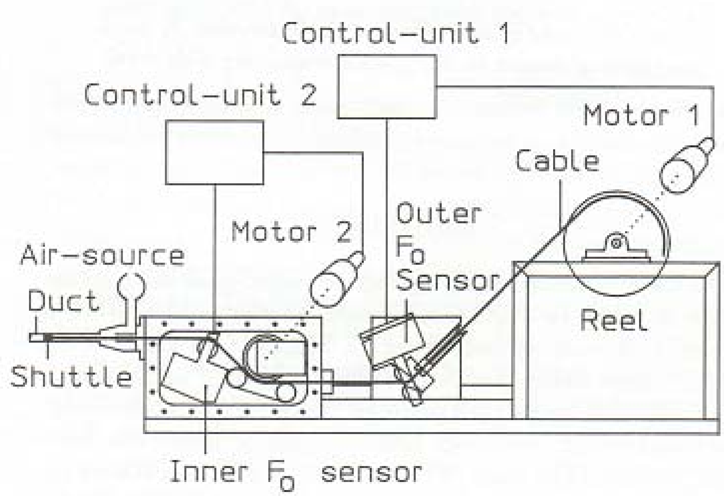

Figure 8: Schematic of the looped-trajectory field trial

In figure 9 the speed as a function of time is shown. In the first 3.5 s the cable is in the part (45 m) in which only 5 right-angled curves are present. In that case the force at the shuttle is capable to pull (as in the old pulling-technique) the cable along the duct. Hence the speed remains at it's maximum of 15.5 m/s, as can be seen in figure 9. Then, when entering the loops, the pulling effect of the force at the shuttle is not sufficient anymore to pass all the curves. Now the sliding-on-inertia condition is reached which causes the decrease in speed, shown in figure 9. This decrease in speed corresponds to a deceleration of 1.4 m/s^2 which gives an effective friction coefficient of 0.14. When the end of the duct is reached the cable speed has dropped to 9.5 m/s. It was not easy to increase the maximum speed and the installation length with this experimental setup. This is due to the limited power (1 kW) of the motors which makes controlling very difficult. The trajectory was however such that traditional pulling of a cable was far from possible.

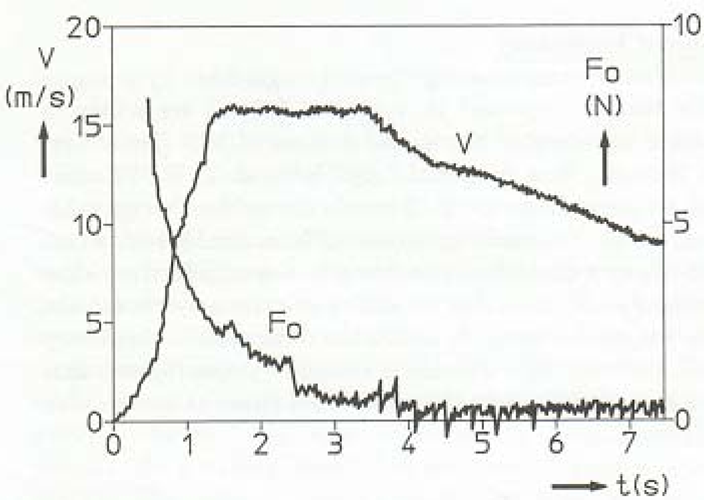

Figure 9: Speed v and effective cable tension F_0 as a function of time t in the looped-trajectory field trial

Conclusions

With the described ultra-high-speed method for the installation of cables in ducts much longer lengths can be installed than with existing techniques. A length of 10 km of fibre-optic trunk cable can be installed, according to theory, in one "shot" taking only 2 minutes. Since the "capstan-effect" is avoided this result will also be obtained in curved duct-trajectories. The mass of the cables is not of importance for the functioning of the described installation-method. Hence any cable (e.g. copper telecommunication- or power-cables) with the same maximum-pulling-force to weight ratio as for a fibre-optic trunk cable can be installed with the same performance. The theory is proved by scale-model field trials in straight- and looped-trajectories. Here 1536 m of cable is installed in 2 minutes and 5 right-angled curves and 6 loops are passed in 7 seconds respectively. With the described technique a lot is possible and much money can be saved, but also a lot of development is still necessary. The friction coefficients between cable and duct are measured. The fact that lubrication causes an increase in friction at high speed explains some deviating results. The friction remains constant when a "dry-lubricated" duct is used.

Acknowledgements

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Appendix

Friction-coefficient

Measurements of friction coefficients between cable and duct are performed with equipment as shown in figure 10. The duct which has to be tested is cut into two halves along its length. One part is attached to the rim of a bicycle-wheel, in a rim-similar way and with a smooth joint. A sample of cable is placed along 90° of this "duct-rim". A weight is attached at one side of the cable while the other side of the cable is attached to a load cell (see figure 10). When the wheel is rotating with a certain speed v (at the rim) the friction coefficient between the cable and duct for this speed follows from F_1 and F_2[1]. Care has been taken that the weight is low and the measuring time is short to avoid heating of cable and duct, especially at high speeds, as much as possible. Large amounts of lubricant cannot be tested at high speeds of the wheel because a lot of it is swept away then.

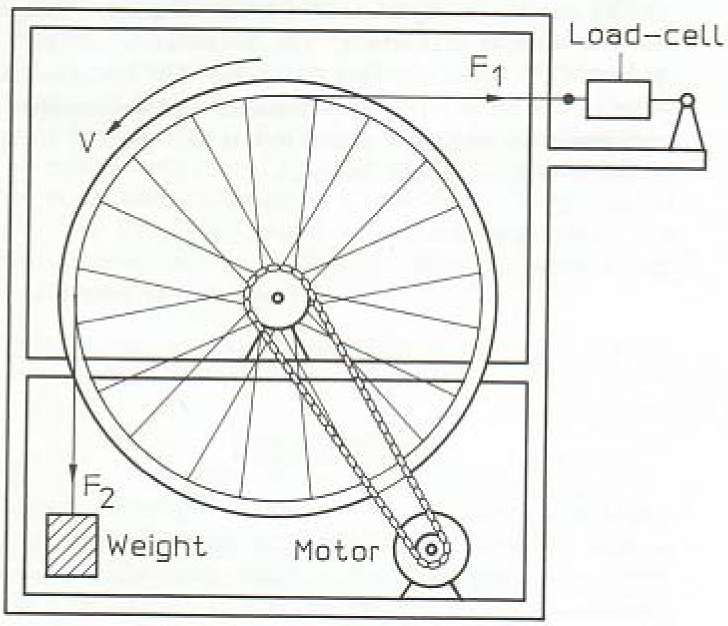

Figure 10: Experimental setup to measure the friction coefficient between cable and duct for different speeds

The cable which is used in the test is the same PVC-jacketed single-fibre cable as is used in the field trials. Two kind of ducts, both with inner and outer diameters of 12 and 16 mm respectively, are used. The first one is made out of pure HDPE and is tested dry, with paraffin oil and with water (in the latter case a cable with HDPE-jacket was used). The second duct also consists of HDPE, but has a solid "lubrication" inner-layer.[6] This duct is only tested dry. The experimental results are given in figure 11.

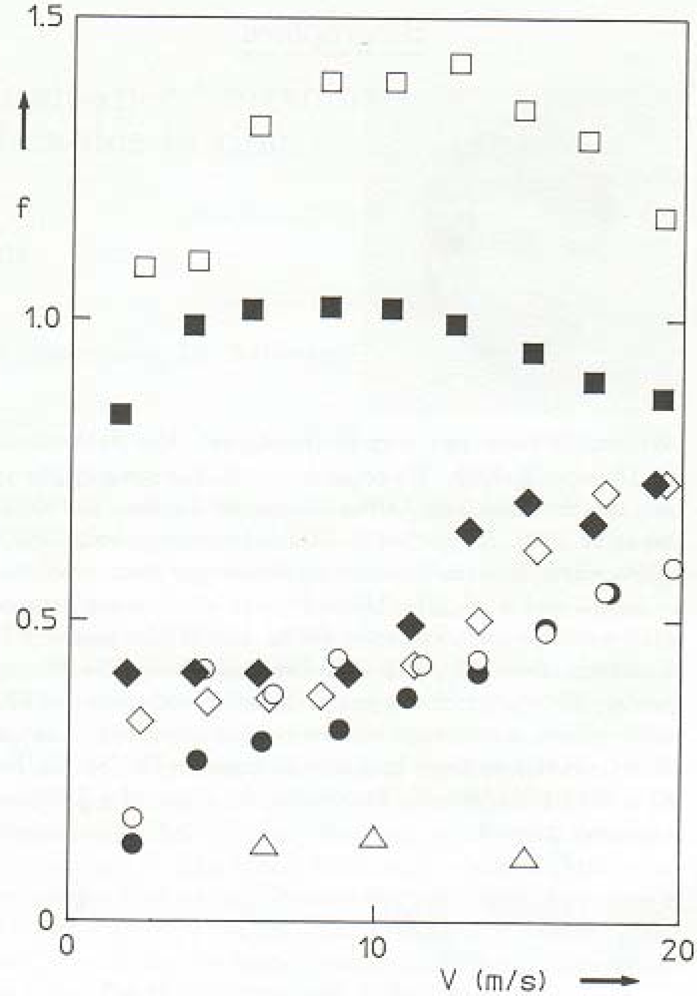

Figure 11: Friction coefficient between cable and duct as a function of speed for a PVC-jacketed cable with dry- (rhombi) and lubricated- (squares=paraffin oil and triangles=water) HDPE ducts and also for "dry-lubricated" HDPE ducts (circles). Weights of 40 and 100 grams are used, indicated by open and solid symbols respectively

From figure 11 it is clear that lubrication with paraffin oil causes an increase in friction, contrary to the situation at lower speeds.[7] This can be explained by a speed-dependent lubricant-viscosity friction. Since this friction does not depend on the force at which the cable is pushed against the duct-wall its effect is higher for lower weights, as can be seen in figure 11. The friction coefficient for dry ducts is much lower, but still increases with speed. Also when using "dry-lubricated" ducts the friction coefficient, which is lower now, increases with speed. This increase with speed can probably be explained by heating of cable and duct. This is supported by the fact that cooling with a slight amount of water results in low friction coefficients at all speeds. Moreover the looped-trajectory field trial, in which the tension in the cable is much smaller (and hence the heat production is less), indicates that the friction coefficient between cable and "dry-lubricated" duct is only 0.14.

Biographies

Willem Griffioen was born in Oegstgeest, The Netherlands, on October 8, 1955. He received his M.S. degree in physics and mathematics from Leiden University, Leiden, The Netherlands, in 1980. He worked at Leiden University from 1980 to 1984, where he investigated macroscopic quantum properties of liquid and solid $^3He/^4He$-mixtures at ultra-low temperatures and in high magnetic fields. In 1984 he joined PTT Research, Box 421, 2260 AK Leidschendam, The Netherlands. His work includes research and development of fibre optic cables, installation techniques and reliability of optical fibres. At this moment he works at Ericsson Cables AB, Box 457, 824 01 Hudiksvall, Sweden in the scope of a half-year-exchange project.

Geert Jan Prins was born in Sidderburen, The Netherlands, on January 13, 1938. He received his B.S. degree in 1965 at Rotterdam, and the B.S. degree in measuring- and control-technique in 1973 at Dordrecht, both in The Netherlands. From 1961 he worked at the Waterloopkundig Laboratorium and at TNO at Delft, a.o. on the development of ship-manoeuvring simulators. From 1973 he was the head of the consultant department of a sub-contractor company for soil working at Halfweg, The Netherlands. In 1981 he joined PTT Research, Box 421, 2260 AK Leidschendam, The Netherlands. His work includes the development of automatic processing of postal letters and parcels, control-systems and installation techniques.