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Theory, Software, Testing and Practice of Cable in Duct Installation

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Abstract

Cables can be installed into ducts by pushing, pulling, blowing and floating, or a combination of those techniques. The distances reached per installation unit depend on the installation technique, on the cable and duct parameters and on the duct trajectory. Installers need test methods, theory and software to estimate the installation distances for the different situations. In this paper a review is given of the different cable in duct installation techniques, their typical applications and their typical installation lengths and installation forces. Also a review is given of the theory for the different installation techniques. Furthermore the existing test methods are reviewed, with their shortcomings. The possibilities of the software, based on the presented theory, with which the distances per installation unit can be estimated for the practical situations, are discussed. The software is illustrated by a typical installation example.

Keywords: Optical cable; duct; coefficient of friction; jetting; blowing; floating; pulling; pushing; software.

1. Introduction

Cables (power cables, symmetrical pair/quad cables, coaxial cables, fibre-optic cables, microduct cables, microduct fiber units and microducts, either one or a bundle) can be installed into ducts (protected ducts, sub-ducts, microducts) by pushing, pulling, blowing and floating, or a combination of those techniques. The distances reached per installation unit depend on the installation technique, on the cable and duct parameters and on the duct trajectory. Sometimes ducts are occupied with resident cables and additional installation of a new cable (or microduct bundle) is required. Installers need aids to estimate the installation distances for the different situations:

- Test methods to obtain the relevant parameters.
- Theory and/or software to calculate the installation distances per installation unit.

In this paper a review is given of the different cable in duct installation techniques, their typical applications and their typical installation lengths and installation forces. Also a review is given of the theory for the different installation techniques. Furthermore the existing test methods are reviewed, with their shortcomings.

Software, based on the presented theory, can be used to distill the effective coefficient of friction (COF) between cable and duct from installation reference tests. With the same software the distances per installation unit can be estimated for the practical situations. In this paper the possibilities and limitations of the current software are discussed. The software is illustrated by a typical installation example.

The theory for installation of optical cables has been described in [1,2,3]. A summary is given in this paper, extended with the theory for additional installation, the effect of "less than real bends" and bundle blowing, the latter two derived in Appendix A and B of this paper, respectively. The theory for additional installation was first derived in [4] and later simplified in [5].

2. Basic Equation

For a cable installed in a duct the general equation for the change in the compressive (tensile defined negative) installation force dF on the cable over a section dx along the duct is given by [1]:

$$\frac{dF}{dx} = f\sqrt{(W\cos\alpha)^2 + (\mathrm{T}F - W_B)^2 + \left(\mathrm{B}F^2\right)^2} + W\sin\alpha - \frac{dF_{blow}}{dx} \quad (1)$$

Here f is the coefficient of friction between cable and duct, W the weight of the cable per unit of length, α the slope of the duct with the horizontal and F the local compressive force in the cable. The symbol T represents the effective change in direction of the duct per unit of length (one can distinguish between individual bends and continuous undulations, the latter best characterized by T), the symbol W_B represents the normal force due to the cable stiffness in undulations of the duct trajectory, the symbol B is a buckling constant and dF_{blow}/dx is the blowing force per unit of length. The different contributions to the force in (1) are explained below.

2.1 Effect of Gravity

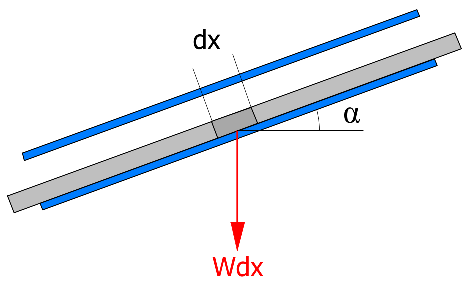

Figure 1. Sloped cable and duct

The effect of gravity is illustrated in Figure 1. Here a straight section of a sloped duct is drawn. Considering only the effect of the weight of the cable the change dF is given by:

$$\frac{dF}{dx} = fW\cos\alpha + W\sin\alpha \quad (2)$$

This is a special case of (1). The fraction of the weight W pointing normal to the duct wall, with cosα, gives the friction force when multiplied by f. The fraction in the axial direction of the duct, with sinα, contributes directly to dF.

2.2 Effect of Change in Direction of Duct

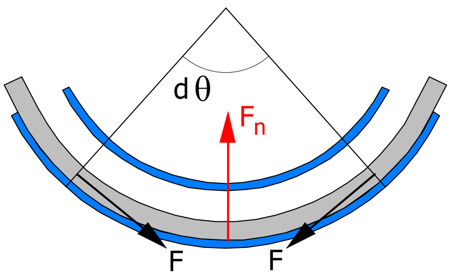

Figure 2. Cable in duct that changes in direction

The effect of a compressive force F due to the change in direction of the duct is illustrated in Figure 2. Here the duct is bent over an angle $d\theta$. The component F_n of the compressive force F in the cable in the direction normal to the duct gives the friction, when multiplied by f [1] (note: sin $(d\theta) = d\theta$ for small $d\theta$):

$$\frac{dF}{d\theta} = fF \qquad (3)$$

This formula can be used for bends of angle θ (see Section 3.1). In the case of undulating ducts (usually the case), continuously over the length, the effective change T in direction of the duct per unit of length can be estimated. In this case (3) is rewritten as:

$$\frac{dF}{dx} = f\mathrm{T}F \qquad (4)$$

For undulations in the horizontal plane the friction is pointed at right angles to the part of the friction force of (2) pointing normal to the duct wall and has to be added quadratically, as can be recognized in (1). For a duct with sinusoidal undulations of amplitude A and period P this change T is given by [1]:

$$\mathrm{T} = \frac{8\pi \mathrm{A}_{eff}}{P^2} \qquad (5)$$

Here $\mathrm{A}_{\mathrm{eff}}$ is the effective cable amplitude, which is $A \pm ½(D_d\text{-}D_c)$, - for pulling, + for pushing (better: TF>W_B, see below), where D_c is the diameter of the cable and D_d the inner diameter of the duct.

2.3 Effect of Cable Stiffness in Duct Undulations

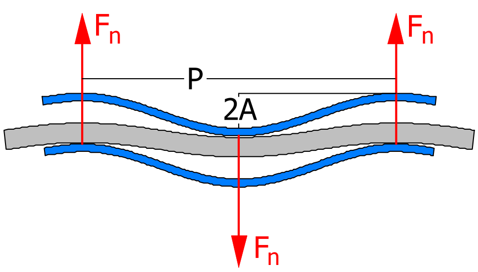

Figure 3. Cable bending under undulations

The cable bends under undulations, when $2A$ is larger than the cable's free space $D_d\text{-}D_c$ in the duct. The cable stiffness causes an extra normal force F_n twice each period P, resulting in an effective force per unit of length W_B, which is derived for the worst case situation of zero compressive force in the cable [1]:

$$W_B = \frac{3(2A - D_d + D_c)B}{4(P/4)^4} \qquad (6)$$

This normal force points in the same direction as the force from the cable compressive force in the undulations and can, hence, be subtracted directly. For tensile forces (negative) they add. This can also be recognized in (1).

2.4 Effect of Cable Buckling under Pushing

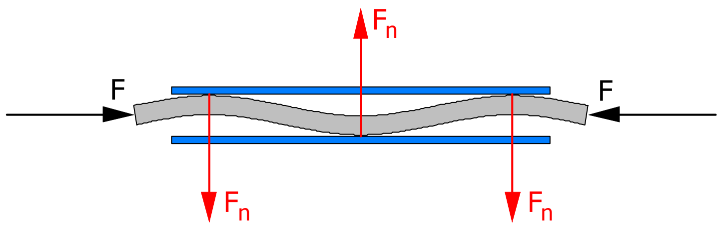

Figure 4. Cable buckling under pushing

Another effect is buckling of the cable when it is pushed. This adds an extra friction force [1]:

$$\mathrm{B}F^2 \qquad \text{with} \qquad \mathrm{B} = \frac{D_d - D_c}{\pi^2 B} \qquad (7)$$

This buckling occurs randomly in all directions and is, hence, added quadratically to the rest, see again (1).

2.5 Effect of Blowing Forces

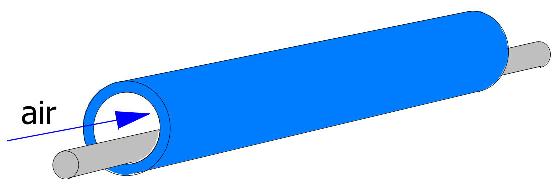

Figure 5. Cable under high speed airflow

When a high speed airflow is forced through the duct, i.e. when compressed air is fed into the duct with cable without using a shuttle at the end of the cable which would block the airflow, the cable experiences propelling forces [1]:

$$\frac{dF_{blow}}{dx} = \tfrac{1}{4}\pi D_c D_d \frac{p_i^2 - p_a^2}{2l\sqrt{p_i^2 - \left(p_i^2 - p_a^2\right)\frac{x}{l}}} \qquad (8)$$

Here p_i and p_a are the air pressures at the inlet and exhaust, respectively, and l is the length of the duct (open at its end). Note that the propelling forces increase towards the end of the duct, due to the expanding airflow. Because of this blowing and pushing forces work in perfect synergy, called jetting.

3. Other Effects

The installation force is found by iteration of equation (1). However, also other effects may have to be taken into account. A few important ones have been listed in this section.

3.1 Bends

In most trajectories not only undulations are present in the duct, but also bends. In bends, which typically act over a short distance, the effect of the change in direction has a larger effect on the force build-up in the cable than the other effects. Integrating equation (3) results in the well known exponential "capstan" formula:

$$F_2 = F_1 \exp(f\theta) \tag{9}$$

Here F_1 and F_2 are the force before and after the bend. The bend multiplies the force by a factor. In some cases, where the forces in the cable are low, also the gravity effect has to be taken into account, as is the case for the "wheel formula" in friction tests [6].

Besides the "capstan" effect also the effect of the cable stiffness in bends is different than in undulations. This has been described in Appendix A. Here a distinction can been made between "real" and small-angle bends. Also the effect is different for a cable that passed the bend and a cable with its head still in the bend. In the latter case not only a friction force is generated, but also an effective repulsive force. The extra forces are just added to the force before the bend.

3.2 Additional Blowing

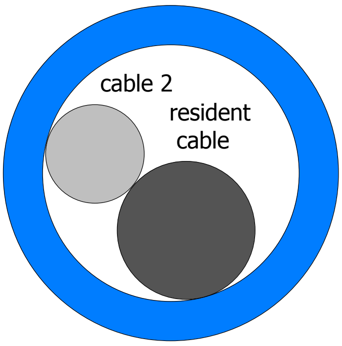

Figure 6. Additional cable in wedge

When a duct is already occupied by a resident cable the cable that is installed additionally experiences extra friction. This is caused by the fact that the new cable falls into the wedge between the resident cable and the duct wall. This causes an increase in the friction by a factor of [5]:

$$f_{wedge} = \sqrt{\frac{(D_c + D_{c2})(D_d - D_{c2})}{D_{c2}(D_d - D_c - D_{c2})}} \tag{10}$$

Here D_c is the diameter of the resident cable and D_{c2} the diameter of the second cable that is additionally installed.

Besides this increase in friction also additional friction is possible at bends. This is rather complicated and not treated in this paper. The resident cable also reduces the flow in the case of blowing or floating (treated further in this paper). In the latter case the second cable might be freed from the wedge, when one cable is heavier and one cable is lighter than water. All of these cases are taken into account in the software presented in this paper.

3.3 Bundle Blowing

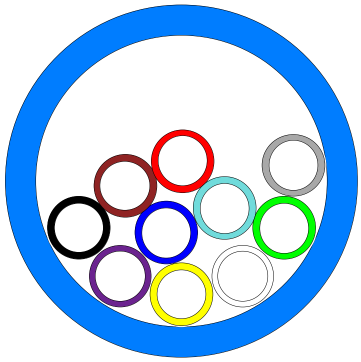

Figure 7. Duct with bundle of microducts

Instead of one cable also a bundle of n cables or, popular today (see e.g. [5]), microducts can be blown in a (protective) duct. This influences the airflow and reduces the blowing force per cable or microduct. The blowing force for a bundle is given by (B5) of Appendix B. For calculation of the installation force n times the mass of a single cable or microduct must be taken.

Jamming of a bundle might also occur [7], not treated in this paper. The software presented in this paper can detect causes of jamming by checking the filling rate of the cables or microducts in the protective duct.

4. Installation Methods

Several techniques are used to install cables in ducts. The most commonly used will be listed in this section and an indication is given how the calculation of the installation force is done.

4.1 Pulling

Pulling a cable in a duct is done by exerting a concentrated force at the cable head. This can be done by means of an air powered plug or a winch rope. The latter has for this technique to be installed first. For pulling in horizontal trajectories equation (1) can be solved analytically, resulting in:

$$F_2 = \frac{W}{\mathrm{T}} \sinh\left[f\mathrm{T}l + \sinh^{-1}\left(\frac{\mathrm{T}F_1}{W} + \frac{W_B}{W} \right) \right] - \frac{W}{\mathrm{T}} \tag{11}$$

Here F_1 is the force at which the cable enters the duct and F_2 is the pulling force (pulling forces defined positive in this equation). The effect of bends is taken by splitting into sections between the bends. The calculation is started with the force F_1 at which the cable is fed into the duct. Then the cable is followed until the first bend. Next the effect of the bend is calculated. Continue until the cable head, where the maximum pulling force is reached.

For inclined trajectories the pulling force has to be calculated by numerical iteration of the equation below:

$$\frac{dF}{dx} = f\sqrt{(W\cos\alpha)^2 + (\mathrm{T}F - W_B)^2} + W\sin\alpha \qquad (12)$$

Application of pulling is in straight routes. Typical pulling lengths are 1500 m per pull for maximum pulling forces around 2000 N.

4.2 Pushing

Pushing a cable in a duct, or rodding, is done by mechanically or manually pushing the cable. It is a technique used for short sections. No installation of a winch rope is needed. But, the forces build up much faster than for pulling, because now also the buckling term adds to this build-up. The pushing force is obtained by numerical iteration of the equation below, which is (1) without blowing:

$$\frac{dF}{dx} = f\sqrt{(W\cos\alpha)^2 + (\mathrm{T}F - W_B)^2 + (\mathrm{B}F^2)^2} + W\sin\alpha \qquad (13)$$

Now the calculation starts at the cable head, with the value of the repulsive force at the head as a starting value. Note that also the intrinsic curvature of the cable adds to the friction at the cable head [1], not treated in this paper but taken into account in the presented software. The iteration is done by following the cable backwards until the pushing equipment at the cable entry.

While the "capstan" effect in bends and undulations leads to an exponential force build-up, the buckling of a pushed cable leads to an asymptotic force build-up [1]. This is known from practice. Pulling further is always possible when you pull harder (although pulling forces might grow rapidly and one has to stop because of the risk of cable breakage). But when pushing is blocked pushing harder does not help anymore.

Application of pushing is in short routes. Typical pushing lengths are 300 m per push for maximum pushing forces around 1000 N.

4.3 Blowing

Blowing, or jetting, a cable in a duct is done by forcing an airflow through the duct while exerting mechanical pushing forces to the cable at the same time [1,2,3]. For blowing the full equation (1) must be iterated numerically. The calculation is done now, instead of from the cable head like with pushing, from near the "critical point" until the cable entry. At the "critical point" the propelling forces of the expanding airflow become bigger than the friction forces [1]. Because the friction at the cable head is largest when it is in a bend the calculation usually starts at the nearest bend near the "critical point" (when resulting in the highest pushing force). Note that the blowing equipment must also supply a pushing force to feed the cable into the pressurized space.

Application of blowing is most economic in long routes. The technique can be used for traditional duct cables as well as microduct cables [11]. Typical blowing lengths are around 2000 m per blow, while lengths up to 3500 m have been reported [13]. Forces on the cable can be kept below 1000 N or less.

4.4 Floating

Floating a cable into a duct is done by forcing water under pressure through the duct while exerting mechanical pushing forces at the same time [9]. Floating behaves almost the same as blowing, with 2 differences: 1) the upward lifting by the water is subtracted from the cable weight *W* and 2) the pressure gradient is linear now (which means that the calculation is done from the cable head again) [1]:

$$\frac{dF_{float}}{dx} = \tfrac{1}{4}\pi D_c D_d \,\frac{p_i - p_a}{l} \qquad (14)$$

Application of floating is in long horizontal routes with access to water. The technique is especially useful for larger diameter ducts and cables, limiting the flow compared to blowing. Typical floating lengths are > 2000 m while lengths over 8 km per float have been reported [9]. Forces on the cable are as with blowing.

5. Software

Software [8] has been written based on the theory presented in this paper. With this software installation lengths can be calculated for pulling, pushing, jetting and floating when all parameters from cable, duct, equipment and trajectory are known.

5.1 Test Methods

Most difficult to measure is the coefficient of friction *f*. Existing laboratory test methods include wheel tests, sloped cable tests, sloped duct tests and bullet tests [6]. It is concluded that those laboratory test methods can be used to compare different cables and ducts but do not supply sufficient reliable information for estimations of practical installations [10].

An alternative is to distill *f* from installation reference tests, depending on the situation either with the ducts on a drum (to be used only for blown-in microduct fibre units) or in a defined trajectory. An example of the latter is the IEC blow reference test described in [11]. This trajectory consists of loops of 100 m length, connected by 180° bends of specified bend radius. The details of the test are then used in the software, choosing a value of *f* that matches the (just) reached length in the test.

5.2 Example

An example is given below with a cable with diameter of 18 mm, weight of 2 N/m and stiffness of 5 Nm^2 in a 40/33 mm duct (same as used in [12]). The duct of 1500 m was laid in loops of 100 m, with specified bend radius of 1.2 m. Blowing with 9.6 bar was (just) successful until the end.

In Figure 8 it can be seen that a match was obtained for a value of *f* of 0.1. Note that a CableJET was used, with a pushing force of 400 N (156 N effective when subtracting the force to feed the cable into the pressurized space).

In Figure 9 the example trajectory is shown for which an estimate of the blowing length is asked. Many bends, with bend radius of 1.2 m, are present. The red lines represent vertical sections. This example trajectory is the same as used in [12].

Figure 10 shows the estimated blowing length for the example cable in the example trajectory. It was blown with 12 bar using a pneumatic SuperJET, with pushing force 1200 N (900 N effective when subtracting the force to feed the cable into the pressurized space). The distance of 2220 m reached is a little higher than the estimated blowing length in [12], where the pushing force was 208 N. For the latter situation Figure 11 shows the installation force (insertion location) as a function of the position of the cable head (duct open at 2000 m). In Figure 11 for the same trajectory also graphs are shown for pushing (insertion location) and pulling (cable head end). The distances reached for pushing and pulling, 450 m and 1100 m, respectively, are clearly less than the blowing length, which reached over 2000 m in this example.

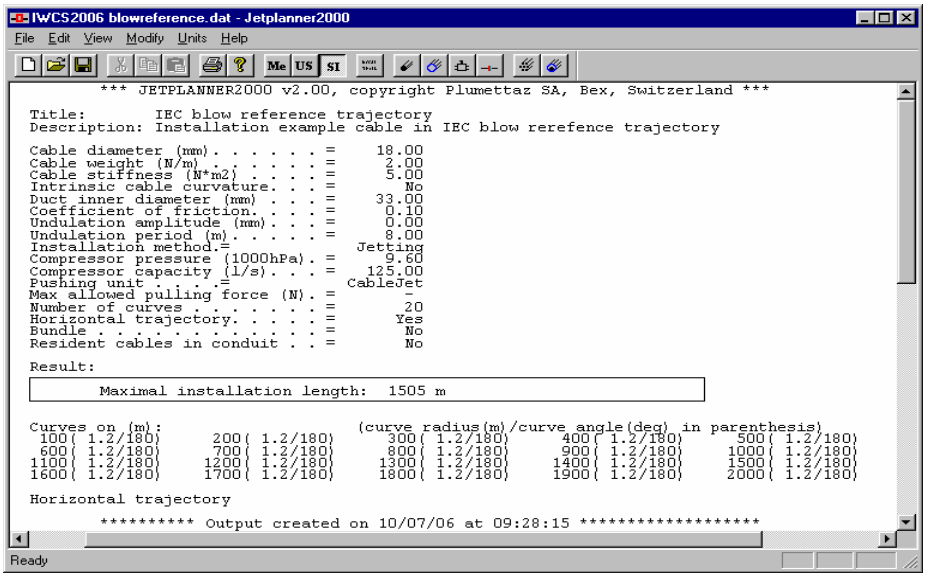

Figure 8. Software result for example cable and duct in IEC blow reference test

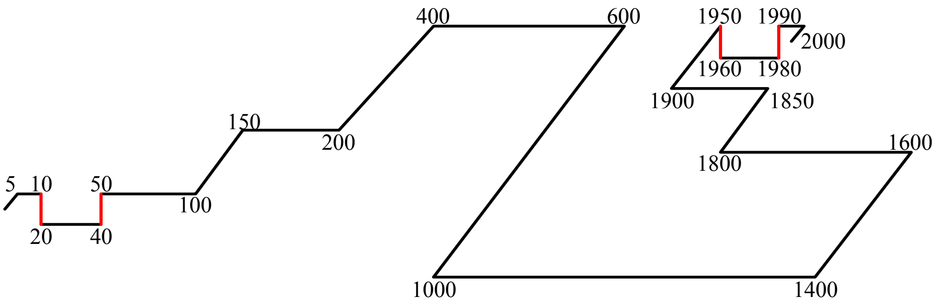

Figure 9. Layout of example trajectory (the red portions are vertical)

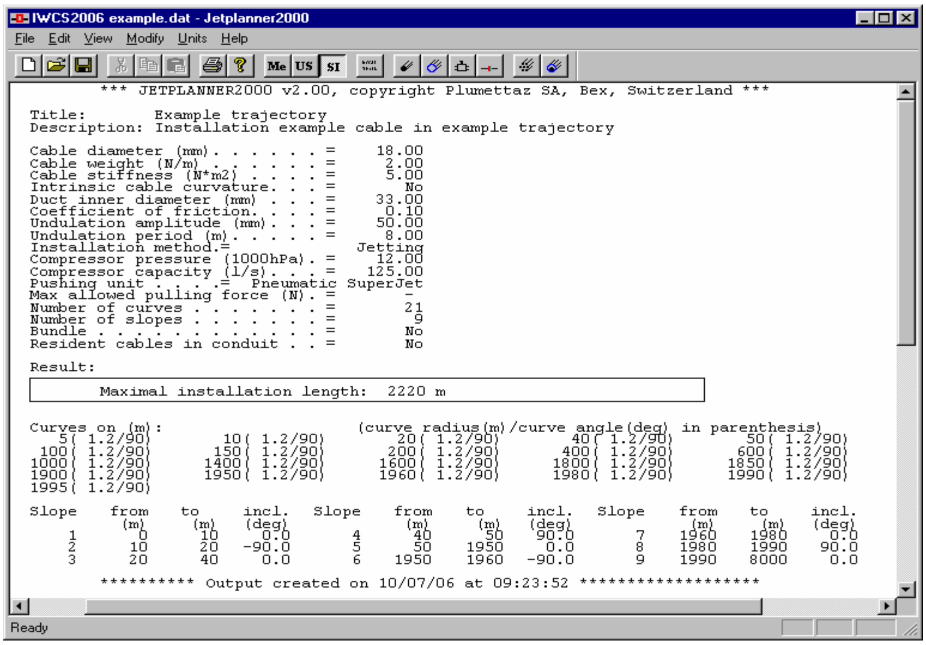

Figure 10. Software result for example cable and duct in example trajectory of Figure 9

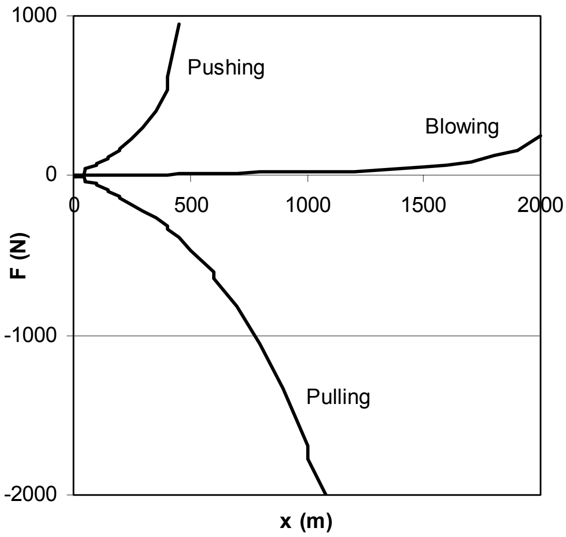

Figure 11. Installation force as function of position of the cable head for pushing, pulling and blowing

6. Conclusions

In this paper a review is given of the different cable in duct installation techniques, their typical applications and their typical installation lengths and installation forces. Also a review is given of the theory for the different installation techniques. Furthermore the existing test methods are reviewed, with their shortcomings. The possibilities of the software, based on the presented theory, with which the distances per installation unit can be estimated for the practical situations, are discussed. The software is illustrated by a typical installation example.

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Appendix A: Force on Cable in Bend

The forces that act on cables moving through small-angle bends in ducts will be derived for a theoretical worst case model were the changes from straight to bent duct and vice versa are abrupt. This was done earlier for "real bends" [1] where the cable has reached the curvature of the bent duct. Also the worst case situation is considered that no longitudinal forces are present in the cable. Such worst case situations may exist in reality, e.g. for well balanced floated cables where occurring forces have been reduced to almost zero, the effect of the cable stiffness in bends remaining as the dominant force. In cases where other forces are higher the forces derived here will be a little too large, but also not dominating anymore.

A1. Normal Forces

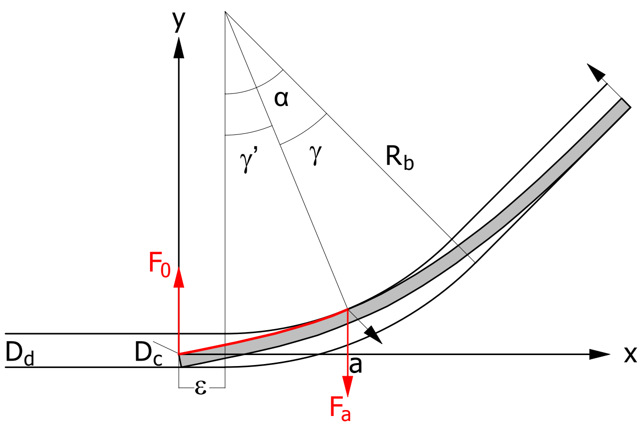


Figure A1. Normal forces due to cable stiffness when cable head passes a small-angle bend.

The curvature of a cable, the inverse of its bending radius R, is equal to the quotient of the bending moment acting on that cable and the stiffness B of that cable [1]:

$$\frac{1}{R} = \frac{F_0}{B} x \tag{A1}$$

Here F_0 is the normal force from the duct wall acting on the cable at $x = 0$, see Fig. A1. It is counteracted at $x = a$ with the force F_a. For small angles dy/dx (or y') remains small and the curvature can be written as:

$$\frac{1}{R} = y'' \tag{A2}$$

Combining (A2) and (A1) and integrating with boundary condition $y'(a) = \tan(\gamma') \approx \gamma'$ gives:

$$y' = \frac{F_0}{B}\left(\tfrac{1}{2}x^2 - \tfrac{1}{2}a^2\right) + \gamma' \tag{A3}$$

Integrating again with boundary condition $y(0) = 0$ gives:

$$y = \frac{F_0}{B}\left(\tfrac{1}{6}x^3 - \tfrac{1}{2}a^2 x\right) + \gamma' x \tag{A4}$$

From Fig. A1 can be seen:

$$a = \varepsilon + R_b \sin\gamma' \approx \varepsilon + R_b\gamma' \tag{A5}$$

Here R_b is the bend radius of the duct and ε the cable length that entered the straight duct section (note that the duct changes abruptly from bent to straight in the model used, which is a worst case assumption). From (A4), with boundary condition $y(a) \approx D_d - D_c + R_b(1-\cos\gamma) \approx D_d - D_c + \frac{1}{2}R_b\gamma^2$, where D_c is the cable diameter and D_d the duct (inner) diameter, then follows:

$$F_0 = 3B\frac{\frac{1}{2}R_b\gamma'^2 + \gamma'\varepsilon - (D_d - D_c)}{(\varepsilon + R_b\gamma')^3} \tag{A6}$$

A.1.1 Cable Head In Bend. In this situation the maximum force F_0 is relevant. This is reached in fact for the cable head just after the bend (the cable still bends further after entering the straight section after the bend), for a value of ε_{bh} given by:

$$\varepsilon_{bh} = \tfrac{3}{2}\frac{D_d - D_c}{\gamma'} - \tfrac{1}{4}\gamma' R_b \tag{A7}$$

In Fig. A2 the force F_0 from (A6) is shown as a function of ε for the situation of Fig. 1 (numerical example of appendix A of [1], with a D_c of 10 mm, D_d of 26 mm and B of 1 Nm^2, only now R_b = 0.25 m, and α = 45°, close to a "real bend"). The maximum is reached for the value of ε given by (A7). After that the force F_0 decreases until the situation that the cable head passed the bend is reached (end of the curve) and the cable reaches a horizontal position, see further.

From (A6) and (A7) it follows:

$$F_0 = \frac{4B\gamma'^3}{9\left(D_d - D_c + \frac{1}{2}\gamma'^2 R_b\right)^2} \tag{A8}$$

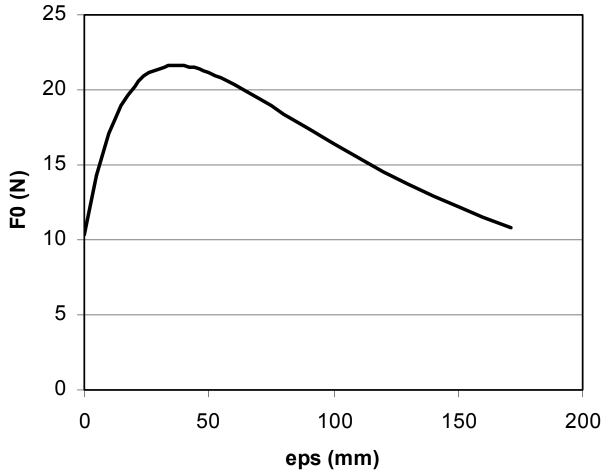


Figure A2. Force F_0 as a function of ε for the situation of Fig. A1.

A.1.2 Cable Head Passed Bend. This situation is reached when $y'(0) = 0$. In Fig. A1 the mirror copy (other side of the bend) is shown for this situation. With (A6) then follows that, realising that for this case γ is written without accent, this situation is reached for a value of ε_b given by:

$$\varepsilon_b = 3\frac{D_d - D_c}{\gamma} + \tfrac{1}{2}\gamma R_b \tag{A9}$$

From (A6) and (A9) it follows:

$$F_0 = \frac{2B\gamma^3}{9\left(D_d - D_c + \frac{1}{2}\gamma^2 R_b\right)^2} \tag{A10}$$

This is half that of (A8), in the case of equal γ and γ'.

A.1.3 Equal γ and γ'. This is the case when for both situations the bend radius R is the same at $x = a$. This is found from (A1) and (A2) for $x = a$ with (A5) substituted. Further substituting (A7) and (A8) or (A9) and (A10) for the cable head in the bend and the cable head passed the bend, respectively, both give the same solution, here expressed in γ:

$$\frac{1}{R}(a) = \frac{2\gamma^2}{3\left(D_d - D_c + \frac{1}{2}\gamma^2 R_b\right)} \tag{A11}$$

This means that, at least for the relevant forces, the angle α is nicely cut into two equal angles γ and γ':

$$\gamma' = \gamma = \tfrac{1}{2}\alpha \tag{A12}$$

The forces F_0 for the cable head in and passed the bend then, still for small angles, simply follow from (A8) and (A10), respectively.

A.1.4 Transition Small Angle to "Real Bend". When R in (A11) becomes equal to R_b it can no longer decrease. In this case the angle is large enough for a real bend and the cable follows the curvature of the duct for some length. From (A11) and (A12) the critical angle α_{rb} follows where a real bend starts:

$$\alpha_{rb} = 2\sqrt{\frac{6(D_d - D_c)}{R_b}} \tag{A13}$$

This angle was already known from [1]. Note that in that case it follows from (A7) and (A9) that:

$$\varepsilon_{bh} = 0 \qquad \text{and} \qquad \varepsilon_b = \sqrt{6(D_d - D_c)R_b} \tag{A14}$$

The left part is to be expected: For a real bend the cable is fully bent and is not expected to bend further when entering the straight section after the bend. Substituting in (A8) and (A10), respectively, gives:

$$F_0 = \frac{B}{\sqrt{6(D_d - D_c)R_b^3}} \tag{A8'}$$

$$F_0 = \frac{B}{2\sqrt{6(D_d - D_c)R_b^3}} \tag{A10'}$$

These are the same equations as found earlier for real bends [1].

A2. Friction and Counter-Acting Forces

A.2.1 Cable Head Passed Bend. In this situation the equal but opposite normal forces F_0 and F_a, given by (A10), both appear two times, when entering and when leaving the bend. To obtain the friction force these forces are multiplied by the coefficient of friction f, resulting in a total friction force F_b of:

$$F_b = \frac{8fB\gamma'^3}{9\left(D_d - D_c + \frac{1}{2}\gamma'^2 R_b\right)^2} \tag{A15}$$

For a real bend the equation from [1] is found:

$$F_b = \frac{2fB}{\sqrt{6(D_d - D_c)R_b^3}} \tag{A15'}$$

A.2.2 Cable Head In Bend. In this situation the normal forces F_0 and F_a from (A10) appear once, when entering the bend. When leaving the bend the 2 times higher normal forces F_0 and F_a from (A8) appear. This resuls in a total friction force F_{bh} of:

$$F_{bh} = \frac{4fB\gamma'^3}{3\left(D_d - D_c + \frac{1}{2}\gamma'^2 R_b\right)^2} \tag{A16}$$

For a real bend the equation from [1] is found:

$$F_{bh} = \frac{3fB}{\sqrt{6(D_d - D_c)R_b^3}} \tag{A16'}$$

When the cable head is in the bend also an effective counter acting force is present. When F_0 is pointed normal to the duct the force F_a will make an angle tilted by γ', resulting in a compressive longitudinal force $F_a \sin(\gamma') \approx F_a\gamma'$ in the cable. In the case of the cable head passed the bend those forces are of equal magnitude for entering and leaving the bend and cancel each other. In the case of the cable head in the bend, however, they do not cancel, as can be seen in Fig. A1 where the forces for the cable head in the bend (red arrow) are twice as large as the forces for the cable head passed the bend (black arrow). Hence half of the longitudinal force for the cable head in the bend remains as an effective counter acting force F_{ch}, found using (A8):

$$F_{ch} = \frac{2B\gamma'^4}{9\left(D_d - D_c + \frac{1}{2}\gamma'^2 R_b\right)^2} \tag{A17}$$

For a real bend the equation from [1] is found:

$$F_{ch} = \frac{B}{2R_b^2} \tag{A17'}$$

A3. Numerical example

Using the values from the numerical example in Appendix A of [1] (W = 1 N/m, D_c = 10 mm, B = 1 Nm^2, D_d = 26 mm, R_b = 1 m and f = 0.2) the following values are found for different angles α (2 times γ; the angle α for a real bend in this case is 35.5°):

Table A1. Forces in bend for "standard cable"

α (°)	10	20	25.1	30	35.5	40
F_b (N)	0.30	0.97	1.17	1.26	1.29	
F_{bh} (N)	0.45	1.45	1.75	1.89	1.94	
F_{ch} (N)	0.03	0.21	0.32	0.41	0.50	

The same calculations for the "heavy weight" cable from Appendix A of [1] (different are W = 3 N/m, D_c = 18 mm, B = 3 Nm^2; the angle α for a real bend in this case is 25.1°):

Table A2. Forces in bend for "heavy cable"

α (°)	10	20	25.1	30	35.5	40
F_b (N)	2.54	5.25	5.47			
F_{bh} (N)	3.81	7.88	8.22			
F_{ch} (N)	0.28	1.15	1.50			

Appendix B: Bundle blowing

The blowing force consists of two parts, the hydrostatic part F_{hs} and the hydrodynamic part F_{hd} [14]. They depend on the diameters D_d of the (inner) duct and D_c of the cable and of the pressure gradient dp/dx. The hydrostatic force is just the product of pressure gradient and cross-sectional area of the cable:

$$\frac{dF_{hs}}{dx} = \frac{\pi D_c^2}{4}\frac{dp}{dx} \tag{B1}$$

The hydrodynamic force is found by dividing the force on the cross-sectional area of the annulus between cable and duct-wall in a portion acting on the duct wall and a portion acting on the cable. The ratio of these two is proportional to their surfaces, i.e.:

$$\frac{dF_{hd}}{dx} = \frac{\pi(D_d^2 - D_c^2)}{4} \frac{D_c}{D_d + D_c} \frac{dp}{dx} = \frac{\pi D_c (D_d - D_c)}{4} \frac{dp}{dx} \quad \text{(B2)}$$

The total blowing force dF_{bl}/dx is equal to the sum of the hydrostatic and hydrodynamic force:

$$\frac{dF_{blow}}{dx} = \frac{\pi D_c D_d}{4} \frac{dp}{dx} \quad \text{(B3)}$$

This is the same formula as (8) and holds for one cable only. For a bundle of n cables the blowing force is different. For the hydrostatic force everything remains the same per cable (each cable will see the same pressure drop over its cross-section). But, for the hydrodynamic force both the annulus and the division over duct-wall and cables need to be corrected. For the total hydrodynamic force it follows:

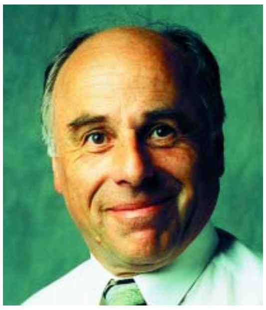
$$\frac{dF_{hd}}{dx} = \frac{\pi(D_d^2 - nD_c^2)}{4} \frac{nD_c}{D_d + nD_c} \frac{dp}{dx} \quad \text{(B4)}$$

Adding to (B1) results in the total blowing force:

$$\frac{dF_{blow}}{dx} = \frac{\pi D_c D_d}{4} n \left[1 - (n-1) \frac{D_c}{D_d + nD_c} \right] \frac{dp}{dx} \quad \text{(B5)}$$

Biographies

Willem Griffioen received an M.Sc. degree in Physics and Mathematics from Leiden University (Netherlands) in 1980 and worked there until 1984. Then he joined KPN Research, Leidschendam (Netherlands). Responsibilities R&D of Outside-Plant and Installation Techniques. He worked at Ericsson Cables, Hudiksvall (Sweden) and at Telia Research, Haninge (Sweden) in the scope of exchange / joint projects with KPN Research. He received his Ph.D. (Reliability of Optical Fibers) in 1995 from the Technical University of Eindhoven (Netherlands). Currently, since 1998, he is product manager at Draka Comteq Telecom, Zuidelijk Halfrond 11, 2801 DD Gouda, The Netherlands.



Gerard Plumettaz received a MS degree in mechanical engineering at the Swiss Federal Institute of Technology, Zürich, in 1970 with an emphasis on machine tool techniques. Joined his family business, Plumettaz SA, CH-1880 Bex, Switzerland, in 1971 and became instrumental in product design, development and marketing. Initial task was to design and develop winching concepts for military tank retrieval. Here specialized winching techniques led to the design of underground placement methods. Today, president and chief operating officer of Plumettaz SA continuing to be active in the pursuit of advanced methods in underground placement/ technology.

Harry Nobach received a M.Sc. degree from the Technical University of Eindhoven (The Netherlands) department of Electrical engineering in 1968. After fulfilling his military duty he joined the Dr Neher Laboratories of KPN (St Paulusstraat 4 Leidschendam, The Netherlands) in 1969. Working area: transmission of wideband signals. In 1995 he moved over to the area of installation techniques, where he worked on the further development of software modeling of cable installation methods especially Jetting. In 2002 he left KPN with early retirement.

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