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Understanding the mechanics of dynamic rope brakes

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Abstract

Dynamic rope brakes are integral elements of the standard belaying equipment. They multiply the hand force of the belayer and convert a fraction of the falling climber’s kinetic energy into thermal energy. As the rope is deflected by the brake, the thermal energy is produced by belt friction. This paper introduces a brake model based on static and viscous belt friction. The contact angles of three different brakes (figure-of-eight, ATC and HMS [Munter hitch]) were determined. These data as well as data taken and/or derived from the literature served as input for the model. The static and viscous belt friction coefficients range between 0.2-0.3 and 0.015-0.04, respectively, for the three brakes. Depending on the magnitude of the friction coefficients, three conditions can be distinguished: 1) no rope slip at high friction; 2) rope slip and stop; 3) critical braking; and 4) continuous rope slip (no stop). The window of the friction coefficients between no slip and critical braking is independent of the hand force. However, the smaller the hand force is, the larger are the friction coefficients at no slip and critical braking. Belayers with smaller hand forces should therefore avoid rope brakes with small static and viscous friction coefficients (like the Figure-of-Eight) and apply the ATC or HMS.

Keywords: mountaineering; rope brakes; belt friction; viscous friction, rope slip, critical braking

1. Introduction

Dynamic rope brakes are an integral part of the standard belaying equipment in rock climbing. Dynamic brakes are characterised by the rope slipping through the brake, thereby they reduce the deceleration of the falling climber and thus the brutality of the arrest when the rope brakes the fall, and multiply the belayer’s hand force allowing control of the rope slip. Rope brakes are tested with “virtual” or “simulated” hands, which supply constant force to the slipping rope on the belayer’s side [1,2,3]. Brakes were modelled by Bedogni [4] and Manin et al. [5]. The former model considers the safety chain as a mass-spring-damper system; the latter replaced the rope damping by a non-linear stiffness and added viscous friction to the last anchor (karabiner). Neither of the two similar models considered viscous friction at the brake. Manin et al. [1,5] defined the force multiplication of the brake by the multiplier \( \beta \), the brake factor. The latter equals the static belt friction \( e^{\mu \theta} \) [5] where \( \mu \) and \( \theta \) are the static friction
coefficient and the contact angle respectively. The brake factor $\beta$, the ratio of rope force on the fall side to maximal hand force of the belayer [5], is allegedly a measure of the brutality of the fall and remains constant during the rope slip [1].

The aim of this study was to investigate the behaviour of rope brakes under consideration of viscous friction, by
- measuring contact angles of three common rope brakes,
- analysing literature data as to hints of viscous friction,
- developing a brake model based on viscous belt friction, and
- comparing model data to literature data.

Figure 1: Rope brakes; (a) ATC (the arrow points at the ridges), (b) Figure-of-Eight, (c) HMS (* = Austrian version, + = German version); rope shanks to the belaying hand point downward and to the climber upward; rope slips upward.

2. Contact angles

We investigated three rope brakes (Fig. 1), the ATC, the Figure-of-Eight (Fo8), and the HMS (Munter hitch, Italian hitch, Cabestan knot / nœud de demi-cabestan). The contact angles were measured on photos taken from various aspects of the brakes. The contact angles, estimated at an accuracy of ±5º, were:
- ATC: 280-300º rope on metal.
- Fo8: 515º rope on metal.
- HMS / “Austrian version” (method recommended by the Austrian Alpine Association): 190º rope on rope (38.78%), 300º rope on metal (61.22%); sum: 490º.
- HMS / “German version” (method recommended by the German Alpine Association): 200º rope on rope (32.5%), 415º rope on metal (67.5%); sum: 615º.

3. Analysis of literature data

Scientific data of fall experiments, conducted with virtual or simulated hands are available in [1,2,3]. Unfortunately, the latter two sources [2,3] were published in the two mountaineering magazines of German speaking countries and thus are not widely accessible. We analysed the data presented in Table 2 of [3], and calculated the brake factor $\beta$ according to [1]. Plotting the brake factor against the rope slip (Fig. 2) shows that the smaller the hand force, the larger is the rope slip and the brake factor. Large rope slip, however, means that the fall arrest is less brutal. Thus, the statement by Manin et al. [1], that the brake factor represents the brutality of the arrest, is incorrect. It is, however, correct when comparing brakes tested at exactly the same maximal hand force.

Extrapolating the brake factor to zero rope slip (Fig. 3), i.e. zero slip velocity, reveals $e^{\mu\theta}$ and, after logarithming and dividing by $\theta$, the static friction coefficient $\mu$.

The value of $e^{\mu\theta}$ of all 3 brakes is very close; ATC: 4.82; Fo8: 5.73; HMS: 5.15. $\mu$ results from the contact angles obtained above: ATC: 0.322, Fo8: 0.194, HMS: 0.192 (Austrian version) and 0.153 (German version). According to the figure on p. 56 of [6], the experimental set-up (simulated hand of [2] and [3]) shows a rope angle closer to the Austrian version, and the corresponding $\mu$ of 0.192 is more likely and closer to the one of the Fo8. As the HMS is characterised by additional rope on rope contact, a $\mu$ smaller than the one of rope on metal (Fo8) is unlikely. Additionally, Figure 3 shows that the brake factor increases with rope slip and thus with slip velocity. This indicates that rope brakes have a viscous, velocity-dependent component. HMS shows the steepest gradient, followed by ATC
and Fo8. The gradient corresponds to the product of slip velocity, viscous friction coefficient and contact angle (see brake modelling below).

Graphs of force data are available in [1] and [5]. These graphs show the load of the last anchor, which is the resultant of the rope shanks on either side of the karabiner, leading to the climber and the rope brake. The force peak shows a peculiar saddle shape which is typical for viscous friction brakes, as will be shown below.

Figure 2: brake factor against rope slip (data of [3]), power fit for different hand forces (A = ATC, 8 = Figure-of-Eight, H = HMS)
Figure 3: brake factor against rope slip (data of [3]), linear fit for three rope brakes (A = ATC, 8 = Figure-of-Eight, H = HMS)
Figure 4: force of last anchor against time, redrawn from Figure 7 of Manin et al. [5]; units and tick marks omitted as only the shape is decisive

4. Analytical model of the rope brake

As the rope is deflected about the rope brake, we apply the belt friction equation

\[
\frac{T_1}{T_2} = \beta = e^{\mu \theta}
\]  

(1)

where \(T_1\) and \(T_2\) are the forces on the side of the falling climber and the braking hand of the belayer, respectively, \(\beta\) is the brake factor [1], \(\mu\) is the static friction coefficient and \(\theta\) is the angle of contact.

Expanding Eq (1) to two contact areas in series, with different static friction coefficients, \(\mu_1\) and \(\mu_2\), and angles of contact, \(\theta_1\) and \(\theta_2\) results in summing up the products of the individual \(\mu\) and \(\theta\)

\[
\frac{T_1}{T_2} = e^{\mu_1 \theta_1 + \mu_2 \theta_2}
\]  

(2)

This type of belt friction typically occurs in the HMS, where the rope is in contact with both metal (karabiner) and rope in series (Fig. 1). The overall friction coefficient \(\mu\) results from

\[
\mu = \frac{\mu_1 \theta_1}{\theta} + \frac{\mu_2 \theta_2}{\theta}
\]  

(3)

Including the velocity-dependent viscous friction \(\eta\) in Eq. (1) yields
\[ \frac{T_1}{T_2} = e^{\mu \theta_1 \mu \theta_2} \] (4)

according to [7], where \( v \) is the velocity of the rope sliding through the brake.

The linear equivalent of Eq. (4) is the Bingham model, a plastic (St Venant’s) and a viscous (dashpot) element in parallel. Although Eq. (4) indicates a series arrangement of static and viscous belt friction, the equivalent linear elements are both connected to the ground (Fig. 5) and have the same displacement and velocity, and thus are in parallel.

Expanding Eq. (4) to two contact areas in series yields

\[ \frac{T_1}{T_2} = e^{(\eta_1 \theta_1 + \eta_2 \theta_2) + (\mu_1 \theta_1 + \mu_2 \theta_2)} \] (5)

Rearranging Eqs. (4) and (5) allows calculating the slip velocity

\[ v = \frac{\log(T_1 / T_2) - \mu \theta}{\eta \theta} \] (6)

and

\[ v = \frac{\log(T_1 / T_2) - \mu_1 \theta_1 - \mu_2 \theta_2}{\eta_1 \theta_1 + \eta_2 \theta_2} \] (7)

where \( \log \) denotes the natural logarithm.

The safety chain from the falling climber to the hand of the belayer was modelled according to Figure 5. Viscous belt friction in the numerical model is represented by Bingham elements in Figure 5. The input parameters were taken from [5]. The viscous friction coefficient of the rope brakes was varied until the rope slip and brake factor matches the data of Figure 3. The instantaneous slip velocity of the model results from solving Eq. (6). The slip condition, represented by a plastic element in Figure 5, is given by \( T_2 \leq HF_{\text{max}} \), where the latter is the maximal hand force.

Figure 5: model of the belaying chain; \( T_1, T_2, T_3 \) = rope forces; \( GF, IF \) = gravitational and inertial forces (direction of the latter depending on the direction of the acceleration vector); \( HF_{\text{max}} \) = maximal hand force; \( m \) = mass of the falling climber (note that belt friction is replaced by equivalent linear elements).
5. Model results and comparison with the literature

Non-viscous rope brake keep the force peak of $T_1$ constant (Fig. 6), as $T_1$ (i.e. $HF_{max}$), $\mu$ and $\theta$ are constants in Eq. (1). In viscous rope brakes, $T_1$ increases with the slip velocity $v$, which is zero at the beginning and end of the slip period. The force peak is saddle-shaped (Fig. 6), comparable to experimental results (Fig. 4). Increasing the viscous friction coefficient $\eta$ reduces the rope slip and thus the slip velocity $v$. The effect on $T_1$ depends on the product of $\eta v$ in Eq. (4). The effect of increasing $\eta$ is more dominating than the reduction of $v$ (Fig. 7) and thus $\eta v$ increases with $\eta$ and so does $T_1$ and the brake factor $\beta$.

The viscous friction coefficient $\eta$ is estimated by matching $\beta$ and the rope slip with the data of [3] in Figure 3. $\eta$ of ATC, Fo8 and HMS are 0.04, 0.015, and 0.04 respectively (Fig. 8).

![Figure 6: family of force-time curves at different viscous friction coefficients $\eta$, $\mu = 0.2$, $\theta = 490^\circ$, $HF_{max} = 250$ N](image1)

![Figure 7: $\theta = 360^\circ$, $\mu = 0.3$, $\eta = 0.1$ and 0.15; $\eta$ increases by 150%, velocity $v$ reduces to 74.4%, $\theta \eta v$ increases by 11.6% (negative rope slip velocity as climber falls downward)](image2)

![Figure 8: data of [3] (bold symbols, solid fit lines) and model data (italic symbols, dashed fit lines), A = ATC, 8 = Figure-of-Eight, H = HMS](image3)

![Figure 9: family of slip speed - time curves at different static friction coefficients $\mu$ (0.065 - 0.39); $\eta = \mu/5$ (comparable to the HMS, where $\mu = 0.2$ and $\eta = 0.04$), $\theta = 490^\circ$, $HF_{max} = 250$ N, $v_0 = -5$ m/s](image4)

![Figure 10: static friction coefficients $\mu$ against hand force at different $v_0$ (m/s); $\eta = \mu/5$, $\theta = 490^\circ$, $v_0$ corresponds to fall heights of 0, 5, 20, 46, 82 and 127 cm; the double arrows define the window of the friction coefficients between no slip and critical braking (window width decreasing with the fall velocity but independent of the hand force)](image5)
Figure 9 shows the influence of $\mu$ on the rope slip velocity. We can distinguish between four braking conditions:
1) no rope slip at high $\mu$ (static condition), rope slip velocity = 0
2) rope slip and stop; rope slip velocity returns to zero with discontinuous deceleration
3) critical braking: rope slip velocity and deceleration return asymptotically to zero
4) continuous rope slip (no stop), terminal rope slip velocity > 0.

Figure 10 displays the conditions graphically. The smaller the fall velocity $v_0$ at the beginning of rope tightening is, the smaller is the window of the friction coefficients between no slip and critical braking. The friction coefficients at critical braking are independent of $v_0$. Equally, the window of the friction coefficients between no slip and critical braking is independent of the hand force. However, the smaller the hand force is, the larger are the friction coefficients at no slip and critical braking.

6. Discussion

Brakes have a viscous friction component as otherwise the rope force would be constant during the rope slip (Fig. 6). The larger the slip velocity, the larger the viscous friction force. In contrast to Manin et al. [1], the brake factor cannot be determined from the maximal hand force, but rather from the actual hand force during belaying (which increases from zero to maximal before rope slip). Equally, the statement by Manin et al. [1], that the brake factor accounts for the brutality of the fall, needs revision, as smaller hand forces result in larger brake factors, as seen from the model’s results and the data of [2] and [3]. Smaller hand forces result in more rope slip and thus in a smooth fall arrest. Belayers with smaller hand forces should therefore avoid rope brakes with small static and viscous friction coefficients (like the Fo8) and apply the ATC or HMS.

The results of the model show that the HMS and ATC produce a higher high viscous friction coefficient $\eta$ than the Fo8. This is possibly due to the rope on rope contact of the HMS and the ridges of the ATC’s rope outlet on the belayer’s hand side (Fig. 1). These ridges are roughly perpendicular to the direction of the rope slip. Furthermore, the rope outlet is tapered and thus the rope is compressed bilaterally when loaded. The lateral contact of the rope with the ridges adds another friction force to the brake’s belt friction. The ridges experience considerable wear after long-term use.

At increased fall heights and velocities, the window of the friction coefficients between no slip and critical braking extends to higher friction coefficients and becomes sufficiently large for efficient braking (Fig. 10). The reduced window size at slow fall velocities is not necessarily a disadvantage, as the friction coefficients at critical braking are unaffected, and the brake may remain at the non-slip state, such that the fall energy is entirely absorbed by the visco-elastic rope, which is perfectly feasible for small fall heights.

The analytical model presented in this paper served to estimate the static and dynamic belt friction coefficients from literature data. The model was validated only with respect to the shape of force-time curves given in the literature [1,5]. The model of Manin et al. [1,5] produces linear segments in the force-time curve which is due to neglecting the dynamic friction coefficient.

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