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Tracking of Flat Belts

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Abstract: When applying flat belts, correct tracking of the belt through the installation has to be assured. Since flat belts are commonly used for conveying and transmission purposes, tracking systems have been well developed, but the ultimate tracking behaviour of the belt can be greatly enhanced by taking special care in the creation of an adequate tracking mechanism. To obtain long-life operation and full value from the equipment, the correct tracking technique plays an important role. This paper deals with two tracking techniques: The skewed and the angled pulley axis. Numerical simulation results are compared with both measurements and an analytical approach. The advantages of numerical simulation compared to experimental tests are ease, convenience and the absence of any safety risk. Compared to analytical approaches the simulation is used for systems for which simple closed form analytic solutions are not possible.

Key words: Flat belt, belt tracking, angled pulley axis, skewed pulley axis.

Nomenclature

b	Belt width
d	Diameter of the pulley
E	Young modulus of the belt
k_A, k_C	Inclination of the belt when leaving the drum
k_B, k_D	Inclination of the belt when approaching the drum
l	Distance between pulley axels
s	Belt feed
v_{belt}	Belt speed
w_A, w_C	Lateral belt position when leaving the drum
w_B, w_D	Lateral belt position when approaching the drum
α	Pulley tilt within the plane of the approaching belt
β	Pulley tilt within the normal plane of the approaching belt
ρ_B, ρ_D	Curvature of the approaching belt
ρ_A, ρ_C	Curvature of the leaving belt
σ	Bending stresses of the belt

1. Introduction

There is a long tradition in using belts, bands and ropes when transmitting power from one shaft to another. The real boom for belts of leather and textiles came during the industrialisation in the 18th century when all machines in a workshop where driven by a single energy source (e.g., water wheel, steam engine). The first step for a fundamental understanding of how power is transmitted was taken by Leonard Euler and Albert Eytelwein in the 18th century [1-2]. It has been analysed what happens to a rope wrapped around a cylinder the so called capstan problem. A major contribution to flat belt mechanics was made by the German professor Grashof [3], in 1883. He divided the contact angle in two parts, the sliding arc, where sliding occurs between belt and pulley, and the adhesive arc, where the belt sticks against the pulley and belt tension is constant. Grashof also discussed the crowning of flat belt pulleys to stabilize sidewise motion. This was the first presentation in literature that dealt with lateral movement of flat belts and side stabilizing effects. In the following decades, flat belt mechanics was focused on power transmission purposes. Speed loss and torque loss due to slip was of major interest. Although the problem of lateral belt tracking has been known for centuries, a rigorous analysis was missing. Tracking effects like angled pulleys and idlers as well as conical pulleys were only known by experience. But what are the mechanics

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behind the axial motion of a flat belt? What belt and pulley properties influence the motion? Renner [4], Koster [5-6], Spaans [7], and Gerbert [8] derived some basic equations and calculated some preliminary results for flat belts running on conical pulleys. An intensive theoretical and experimental analysis of flat belt tracking was launched by Prof. Hoffmann of Vienna Technical University which led to a number of publications [9-16] and, at least, to both analytical and numerical models for the lateral movement of a flat belt due to an angled axis and crowned pulleys.

This paper deals with steering effects often applied when operating strip processing lines. Considering stiff belt materials such as steel, high belt stresses are induced even by small changes in the geometry of the installation. This means that belt tracking can lead to enormous problems when considering belt materials with a high ratio between stiffness (Young's Modulus) and mechanical strength (tensile strength, fatigue strength). Fast and accurate belt guidance requires an appropriate pulley tilt and this leads to high belt stress. For a proper design of the control system, knowledge about these effects is essential to assure stable lateral belt running. The paper is organized as follows: Section 2 discusses steering measures and principles; section 3 introduces flat belt mechanics; section 4 presents theoretic results; section 5 compares measurement with calculation; section 6 gives conclusions.

2. Steering Measures, Principles

It can be observed that flat belts, supported and driven by cylindrical pulleys, are subject to no guiding force. They run in an unstable condition and flat belt pulleys need to be carefully aligned to prevent the belt from moving off. Faults such as asymmetry in the position or shape of the rollers, uneven temperature distribution or acting transverse forces will make the belt run out of true. Running out of line and rubbing against the frame must be strictly avoided. As flat belts have been running on cylindrical pulleys for centuries, a wide range of guiding systems have since been developed to ensure satisfactory belt tracking. These guiding systems are mostly dealt with by experiments and trial and error. In the following, the most important steering measures are presented. Generally, they can be separated according two basic physical principles for the steering of flat belts:

- Form-conditioned implies that the steering effect relies on geometry and normal forces. These methods are based on forcing the belt to track by exerting normal forces directly upon the belt edge or upon special fixed guide strips by lateral limiting rollers, sheaves or guide bars (Fig. 1). It is a simple and cheap technique but only useable for light-duty applications. The transverse rigidity of the belt is limited, thus the edges may deform and wrinkle the belt. Moreover, rapid wear and tear can also occur. But in the case of short wide belts, form-conditioned belt guidance measures are often the only possibility to ensure true running of the belt;
- Force-conditioned implies that the steering effect relies on contact load and friction. These methods are based on relative velocity and a certain surface pressure in the contact area between belt and pulley. In case of a conical tail pulley, the belt moves towards the largest diameter. Applying cylindrical tail pulleys, the direction

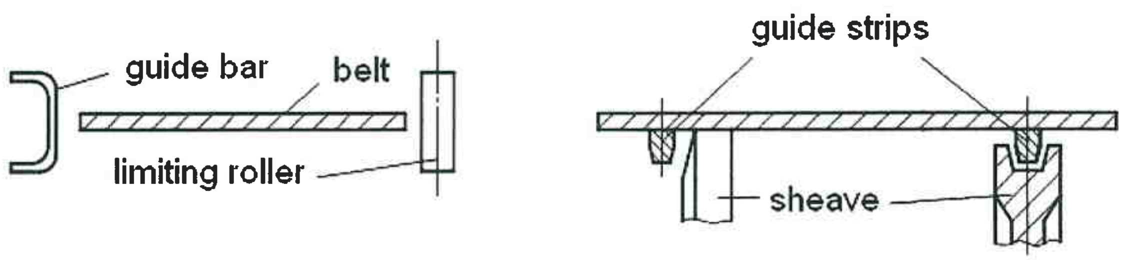

Fig. 1 Form-conditioned steering measures.

of the lateral belt movement depends on the orientation of the pulley axes. Both phenomena are used to control the tracking of flat belts. The induced frictional forces act within the plane of the running belt and cause relatively small lateral shear stresses in comparison to form-conditioned steering measures. In the steel, plastic and paper industries, where materials are produced as wide endless bands, angled pulley axes in combination with belt edge detectors are often used for realizing automatic tracking systems.

Conical drums:

Because flat belts tend to climb towards the higher side of the pulley, pulleys are made with a slightly convex or "crowned" surface (rather than flat) to keep the belts centred, resulting in higher belt stresses (Fig. 2a). This steering effect relies on bending the belt. In general, the lateral belt movement depends on the approach angle, the angle between the belt's centre line and the pulley axes on which the belt comes on. Due to the bending, the belt's approach angle is influenced and causes a lateral belt run out. Cylindrical drums with conical ends are used for independent centring of the running belt. Once the belt edge reaches the conical part of the pulley, the lateral movement will be reversed and the running of the belt tends back to the centre of the pulley [12].

Cylindrical drum, angled within the plane of the approaching belt:

A belt which is guided by a cylindrical drum whose axis of rotation is not perpendicular to the centre line of the installation but within the plane of the approaching belt will run out of true in the direction of lower belt stresses (Fig. 2b). In the following, this effect will be called the angling of pulley axes. As with the conical drum, this effect also relies on bending the belt. A desired lateral belt movement can be achieved by using an adjustable pulley which can be angled by electric or hydraulic drive units. The belt will unroll itself over the drum barrel and the belt's axis performs a helical line. This effect is well known and common applied in industry, mainly for metal belt applications where belt stresses must be controllable. Manipulating the orientation of the pulley axes is an expensive but very low-wear method of ensuring true running of the belt [11].

Cylindrical drum, angled within the normal plane of the approaching belt:

Much less known is the guiding effect of a cylindrical drum whose axis of rotation remains perpendicular to the centre line of the installation but not within the plane of the approaching belt (Fig. 3). In the following, this effect will be called the skewing of pulley axes. Belt tracking can be done by skewing the steering pulley around a steering axis which is parallel to the plane of the running strip and which stands perpendicular to the pulley's axis of rotation. This effect relies on a geometric lateral shift of the belt due to the kinematics of the steering pulley. In contrast to

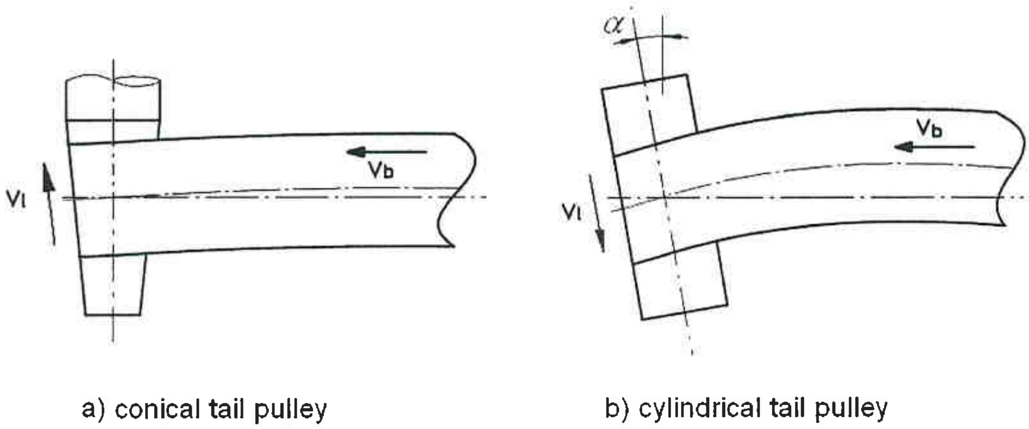

Fig. 2 Aligned conical tail pulley (a) and cylindrical tail pulley angled within the plane of the approaching belt (b).

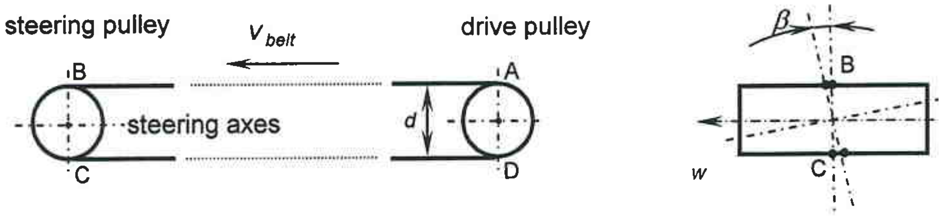

Fig. 3 Skewing of pulley axes.

the steering effects mentioned above, the belt is twisted but bent less. The advantage of this steering measure can be summarised in small steering forces and minimized belt stresses.

Due to the steering direction, which is perpendicular to the running belt direction, the stiff belt will not be bent or extended and steering forces will be minimized. In this case the belt will be bent less and small belt stresses are expected. Due to the kinematics of the steering pulley, the approaching belt is shifted with the movement of the steering pulley.

In general, when applying cylindrical pulleys, two steering mechanisms can be separated, according to the style of cybernetics:

- Proportional action relies on a lateral shift of the belt's exit points due to the kinematics of the pulley. It determines the reaction of the belt to the current pulley tilt;
- Integral action relies on the bending and the shear deformation of the belt due to an angled pulley axis. It determines the reaction based on the sum of recent pulley tilts.

P and *I* value depend on the kinematics of the steering pulley, in particular on the axis of the pulley tilt.

3. Theoretic Approach

The idea of belt mechanics is to develop a theoretical frame, resting on a sound fundamental physical and geometrical base which is able to predict belt performance, in particular, its lateral running behaviour. Let us consider an endless belt, looping a two-pulley configuration according to Fig. 4. It is a convenient arrangement to compare the results of the calculation model with a relatively simple pulley constellation for measurement purposes.

In this paper, two particular steering measures are investigated: Skewing of pulley axes according to Fig. 3 as well as angling of pulley axes according to Fig. 2b. In the considered two-pulley system, a flat belt is looped over both, the drive and the steering pulley. Numerical simulation results are compared with measurements and an analytical approach. The considered test bench comprises a steering pulley which can be skewed vertically and angled horizontally, a drive pulley and an endless running steel belt which is welded head to tail.

Displacing axes of cylindrical pulleys requires quite complex designs with strong drive devices. The pulleys are either hydraulically controlled or, for smaller installations, electrically driven. Investigation is focused on the deformation of a belt segment between the points where it leaves one pulley to that on which it comes on. Since the belt is considered as a beam, its shape is represented by the centre line and the mechanical properties are determined by the length l, the flexural rigidity EJ and the shear rigidity GA of a segment.

An important theme is the interaction of the flat belt with the pulley. In our model, the condition of the approaching belt (lateral position, inclination angle, curvature) is fixed by the pulley and continuously transferred to the exiting area. We assume a belt possessing linear elastic behaviour. The lateral motion of the belt along a pulley axis is determined by the approaching belt shape, i.e., the belt's deformation where the belt goes onto the steering pulley is mainly responsible for the current lateral running.

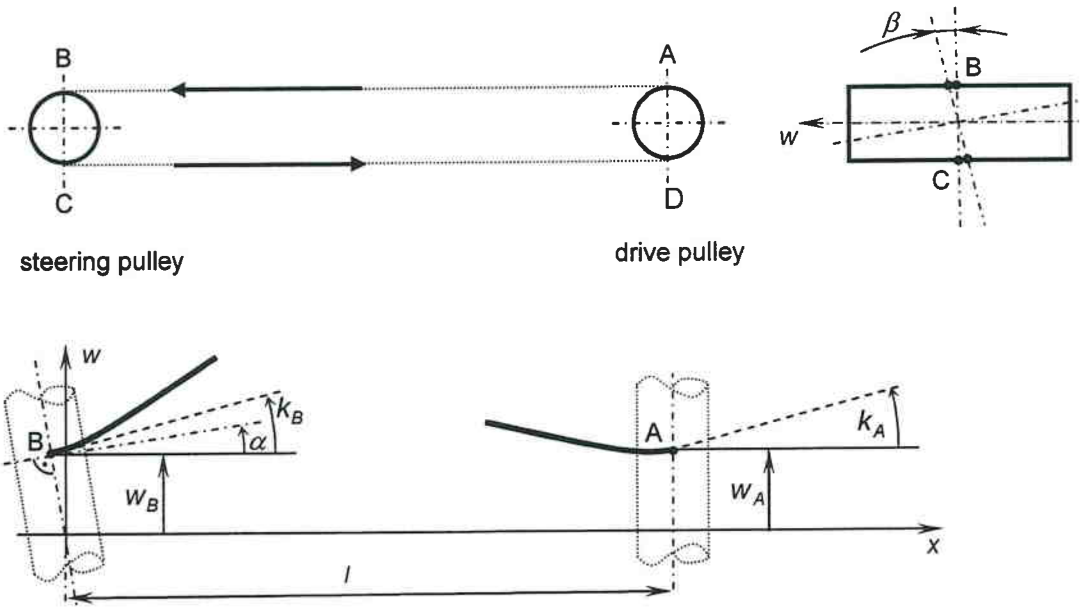

Fig. 4 Flat belt mechanics.

According to the first order bending theory (neglecting the tensioning of the belt), the curvature of the belt section A-B when approaching the steering pulley at B is given by

$$\rho_B = \frac{2}{l} \cdot \left(\frac{3 \cdot (w_A - w_B)}{l} - 2 \cdot k_B - k_A \right) \quad (1)$$

The curvature of the belt section C-D when approaching the driving pulley at D is given by

$$\rho_D = \frac{2}{l} \cdot \left(\frac{3 \cdot (w_C - w_D)}{l} + 2 \cdot k_D + k_C \right) \quad (2)$$

As k_B represents the approaching angle of the belt at B, the lateral motion of the belt when approaching the steering pulley is given by

$$w'_B = k_B - \alpha \text{ respectively } k'_B = \rho_B \quad (3)$$

As the belt section C-D moves in reverse direction, the lateral motion of the belt when approaching the drive pulley at D is given by

$$w'_D = -k_D \text{ respectively } k'_D = -\rho_D \quad (4)$$

As static friction between belt and pulley is assumed, the relationship between the approaching belt and the exciting belt can be written as a linear approximation of the belt section which is in contact with the pulley.

$$w_A = w_D + k_D \cdot \frac{d \cdot \pi}{2} \quad (5)$$

$$k_A = -\left(k_D + \rho_D \cdot \frac{d \cdot \pi}{2} \right) \quad (6)$$

$$w_C = w_B + (\alpha - k_B) \cdot \frac{d \cdot \pi}{2} + \beta \cdot d \quad (7)$$

$$k_C = -\left(k_B - \rho_B \cdot \frac{d \cdot \pi}{2} - \alpha \right) \quad (8)$$

From Eqs. (1)-(8), we get a system of two differential equations for lateral motion of the belt's points of approach.

$$w''_B \cdot l + 4 \cdot w'_B + \frac{6 \cdot w_B}{l} - w''_D \cdot d \cdot \pi + w'_D \cdot \left(2 + \frac{3 \cdot \pi \cdot d}{l} \right) - \frac{6 \cdot w_D}{l} = -2 \cdot \alpha \quad (9)$$

$$w''_D \cdot l + 4 \cdot w'_D + \frac{6 \cdot w_D}{l} - w''_B \cdot d \cdot \pi + w'_B \cdot \left(2 + \frac{3 \cdot \pi \cdot d}{l} \right) - \frac{6 \cdot w_B}{l} = \frac{6 \cdot \beta \cdot d}{l} \quad (10)$$

We can rewrite this in matrix format:

$$\begin{pmatrix} l & -d\cdot\pi \\ -d\cdot\pi & l \end{pmatrix}\cdot\begin{pmatrix} w''_B \\ w''_D \end{pmatrix}+\begin{pmatrix} 4 & \left(2+\frac{3\cdot\pi\cdot d}{l}\right) \\ \left(2+\frac{3\cdot\pi\cdot d}{l}\right) & 4 \end{pmatrix}\cdot\begin{pmatrix} w'_B \\ w'_D \end{pmatrix}+\begin{pmatrix} \frac{6}{l} & -\frac{6}{l} \\ -\frac{6}{l} & \frac{6}{l} \end{pmatrix}\cdot\begin{pmatrix} w_B \\ w_D \end{pmatrix}=\begin{pmatrix} -2\cdot\alpha \\ \frac{6\cdot\beta\cdot d}{l} \end{pmatrix} \tag{11}$$

A more compact form of this matrix equation can be written as

$$M\cdot\underline{w}''+D\cdot\underline{w}'+K\cdot\underline{w}=\underline{f} \tag{12}$$

Eq. (12) represents a linear equation and hence it can also be solved by analytical methods. As *M, D* and *K* are symmetric matrices, the lateral motion of the a belt when looping over two cylindrical drums shows a similar behaviour as the motion of a mass-spring damper system with 2 degrees of freedom.

In particular, we are interested in the steady state lateral belt velocity as it indicates the efficiency of the steering measure. A steady state solution of (12) can be written as

$$\underline{w_\infty}=s\cdot\begin{pmatrix} k_{B\infty} \\ k_{D\infty} \end{pmatrix}+\begin{pmatrix} w_{B\infty} \\ w_{D\infty} \end{pmatrix} \text{ and } \underline{w'_\infty}=\begin{pmatrix} k_{B\infty} \\ k_{D\infty} \end{pmatrix} \tag{13}$$

Substituting these quantities into the differential Eq. (12) results in

$$k_{B\infty}=k_{D\infty}=k_\infty=\frac{1}{2\cdot l+\pi\cdot d}\cdot\left(\beta\cdot d-\frac{\alpha\cdot l}{3}\right)$$

$$w_{D\infty}-w_{B\infty}=\frac{\beta\cdot d}{2}+\frac{\alpha\cdot l}{6} \tag{14}$$

where $k_{B\infty}=k_{D\infty}=k_\infty$ is the belt's angle of approach in the steady state condition, which is proportional to the belt's lateral velocity.

$w_{B\infty}$ and $w_{D\infty}$ describe the belt's lateral displacement in the steady state condition (see Figs. 5-6). As the matrix K is singular, only the relative displacement between point B and D can be derived. This singularity shows the instability of the system as mentioned in section 2.

The angle of approach in the steady state condition according to Eq. (14) quantifies the effectiveness of the steering measure.

Belt stresses:

The belt is being deformed by the lateral motion and stresses develop inside it as transverse load is applied to it by the pulleys. Assuming pure bending and linear elastic material behaviour, the belt stresses due to bending are proportional to the curvature of the belt.

$$\sigma(x)=\frac{-\rho(x)\cdot E\cdot b}{2} \tag{15}$$

As the steady state solution shows a straight approaching belt without any bending, the curvature at the points of approach comes to zero [10]. According to Eq. (1) follows:

$$0=\frac{2}{l}\cdot\left(\frac{3\cdot(w_{A\infty}-w_{B\infty})}{l}-2\cdot k_{B\infty}-k_{A\infty}\right) \tag{16}$$

Hence, the highest belt stresses are expected in the area where the belt leaves the pulleys (A and C, see Fig. 4). According to the first order bending theory, the curvature of the belt section A-B when leaving the drive pulley at A is given by

$$\rho_A=\frac{2}{l}\cdot\left(\frac{3\cdot(w_B-w_A)}{l}+2\cdot k_A+k_B\right) \tag{17}$$

Substituting Eqs. (5)-(6), (14)-(16) in Eq. (17) yields the bending stresses of the exciting belt for the steady state solution:

$$\sigma_{A\infty}=\frac{2\cdot E\cdot b}{l\cdot(2\cdot l+\pi\cdot d)}\cdot\left(\beta\cdot d-\frac{\alpha\cdot l}{3}\right) \tag{18}$$

The assumption of neglecting shear stresses is valid for slender belts, where the width is a small fraction, typically less than 1/10th of the belt's length. With a view to getting manageable analytic expressions, no pre-stress will be considered below. In Ref. [13], the influence of the pre-stress on the belt deformation is discussed.

Considering stiff belt materials such as steel, high belt stresses are induced even by small changes in the geometry of the installation. The quality of a belt tracking system depends, among other things, on the relationship between efficiency and induces belt stresses. With Eqs. (14) and (18), a quality parameter for steering measure of the skewed pulley and the angled pulley can be derived.

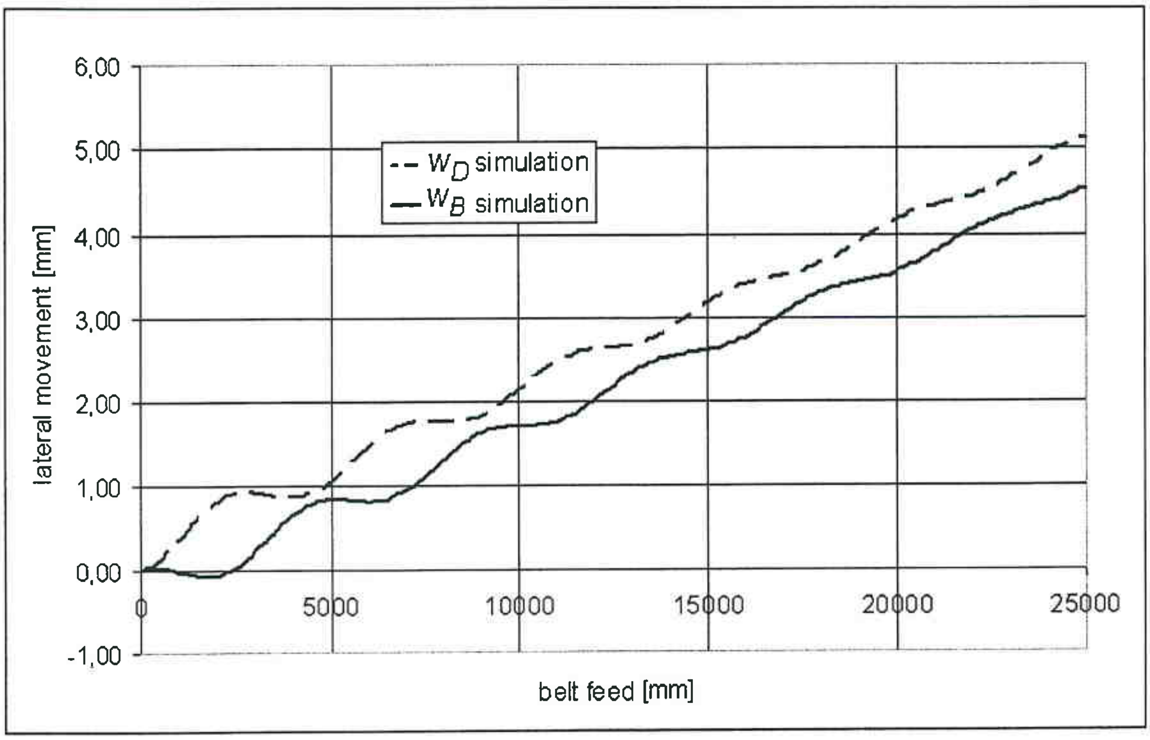

Fig. 5 Numerical solution: Lateral belt movement due to a skewed steering pulley, angled within the normal plane of the approaching belt.

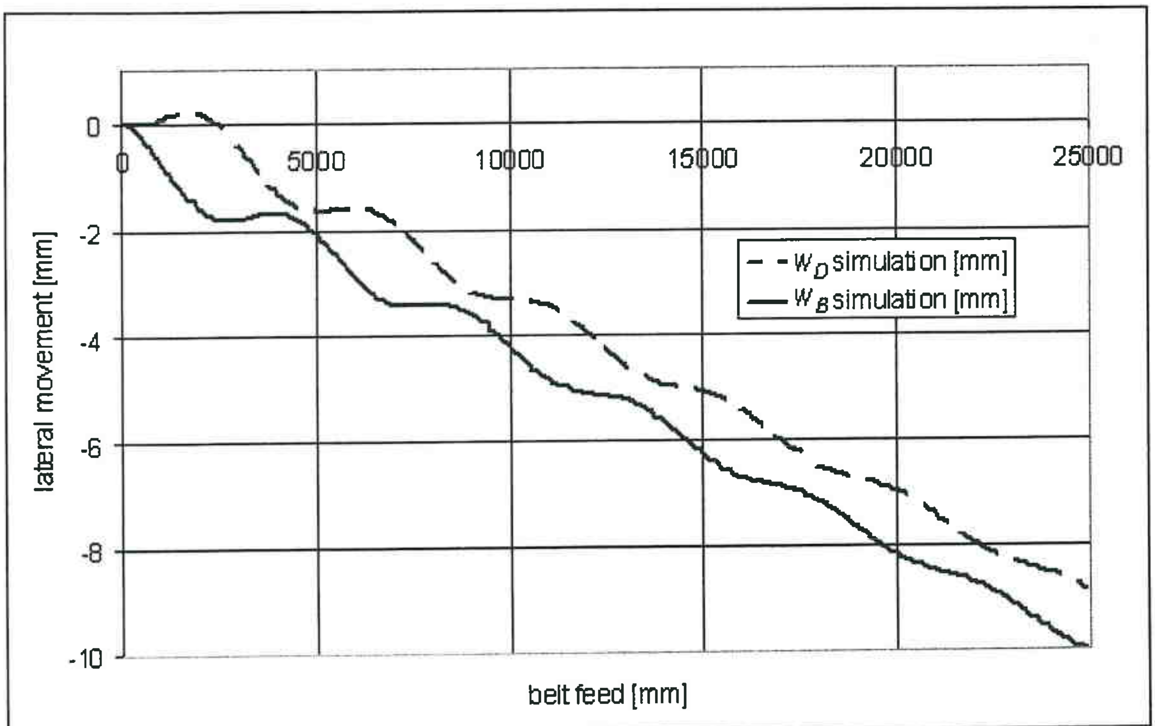

Fig. 6 Numerical solution: Lateral belt movement due to a angled steering pulley, angled within the plane of the approaching belt.

$$\frac{k_\infty}{\sigma_\infty} = \frac{l}{2 \cdot E \cdot b} \tag{19}$$

Eq. (19) shows that under the assumed condition angling and skewing of a cylindrical pulley leads to the same quality factor.

4. Theoretic Results

4.1 Skewing of Pulley Axes

Fig. 5 shows the numerical solution of (12) when applying the skewed pulley according to Fig. 3. Simulation parameters are set according to Table 1. The calculation shows a lateral belt motion of the two points of approach, B and D. The points B and D, where the belt's centre line goes onto the pulley, move along the pulleys axes. After a transient motion, a steady state condition is reached possessing a constant lateral velocity.

From Eq. (14) follows the belt's angle of approach in the steady state condition, which is proportional to the belt's lateral velocity and which quantifies the effectiveness of the steering measure:

$$k_\infty = \frac{\beta \cdot d}{2 \cdot l + \pi \cdot d} = 195 \cdot 10^{-6}$$

From Eq. (14) follows also the lateral displacement of the points of approach in the steady state condition.

$$w_{D\infty} - w_{B\infty} = \frac{\beta \cdot d}{2} = 0.493mm$$

From Eq. (18) follows the belt tension in the point where the belt leaves the pulley.

$$\sigma_{A\infty} = \frac{2 \cdot E \cdot b \cdot \beta \cdot d}{l \cdot (2 \cdot l + \pi \cdot d)} = 5.1 \frac{N}{mm^2}$$

4.2 Angling of Pulley Axes

Fig. 6 shows the numerical solution of (12) when applying the angled pulley according to Fig. 2b. Simulation parameters are set according to Table 2. The calculation shows a lateral belt motion of the two points of approach, B and D. The points B and D, where the belt's centre line goes onto the pulley, move along the pulleys axes. After a transient motion, a steady state condition is reached possessing a constant lateral velocity.

From Eq. (14) follows the belt's angle of approach in the steady state condition, which is proportional to the belt's lateral velocity and which quantifies the effectiveness of the steering measure.

$$k_\infty = -\frac{\alpha \cdot l}{6 \cdot l + 3 \cdot \pi \cdot d} = -381 \cdot 10^{-6}$$

From Eq. (14) follows also the lateral displacement of the points of approach in the steady state condition.

$$w_{D\infty} - w_{B\infty} = \frac{\alpha \cdot l}{6} = 0.961mm$$

From Eq. (18) follows the belt tension in the point where the belt leaves the pulley.

$$\sigma_{A\infty} = \frac{2 \cdot E \cdot b \cdot \alpha \cdot l}{l \cdot (6 \cdot l + 3 \cdot \pi \cdot d)} = 10 \frac{N}{mm^2}$$

5. Comparison Calculation with Measurements

Comparison between the numeric solution of (12) and measurements performed at the test bench of Vienna University of Technology are shown exemplarily in Fig. 7. Starting from the initial condition of parallel pulley axes and a true-running belt, the axle of the steering pulley is angled within the normal plane of the approaching belt according to Fig. 3. After performing a transient motion, the belt reaches a steady state motion with constant lateral velocity. Measurement and calculation show a good accordance.

6. Conclusions

This paper presents a mechanical model for the calculation of a flat belt's lateral running behaviour when going onto a cylindrical pulley. Two steering measures are compared with respect to their effectiveness: Angling the pulley within the plane of the approaching belt (angled pulley) and skewing the pulley within the normal plane of the approaching belt (skewed pulley). Assuming that the first order bending theory is valid for the considered bands, a systems of two differential equation for the belt's lateral motion can be derived. The structure of the system of equation

Table 1 Parameters for the simulation.

Pulley tilt β	Diameter d	Axles distance l	Belt width b	Young's modulus E
2.898×10^{-3}	340 mm	1990 mm	125 mm	210000 Nmm^{-2}

Table 2 Parameters for the simulation.

Pulley tilt α	Diameter d	Axles distance l	Belt width b	Young's modulus E
2.898×10^{-3}	340 mm	1990 mm	125 mm	210000 Nmm^{-2}

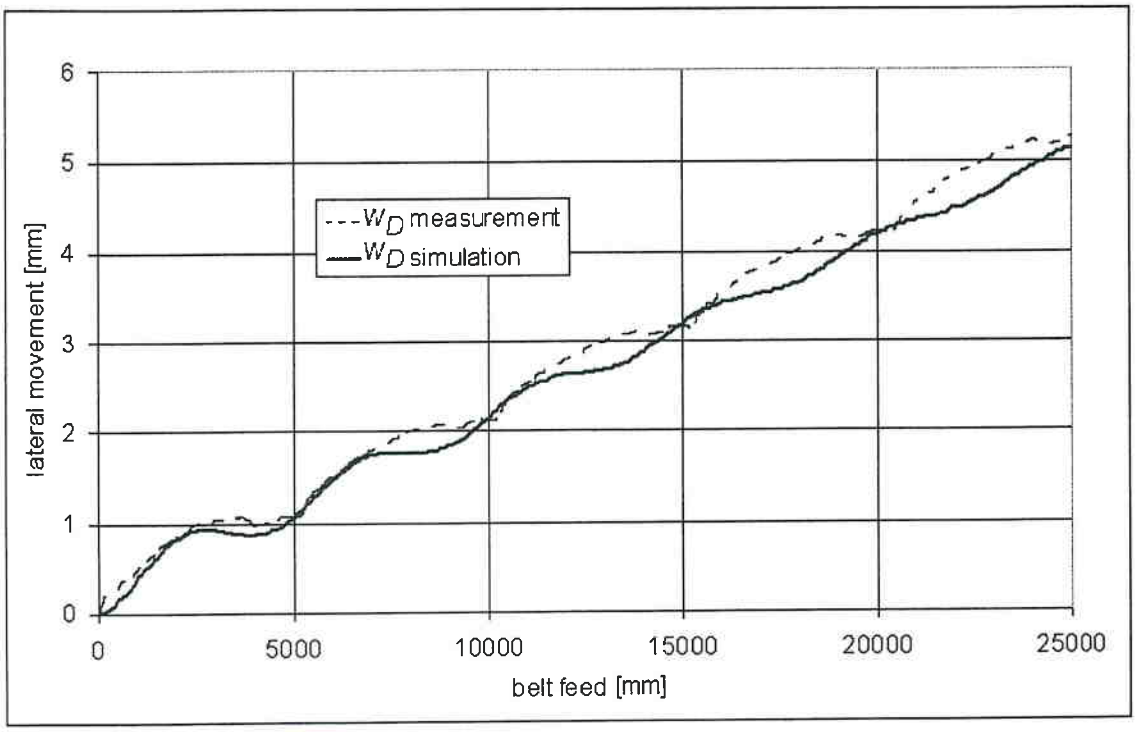

Fig. 7 Comparison between measurement and simulation for pre-tensioned steel belt.

resultant in the singularity of the describing matrix shows the lateral instability of a flat belt when approaching a cylindrical pulley. For the steady state condition, even an analytic solution can derived.

The angle of approach in the steady state condition stands for the efficiency of the steering measure. It depends on the pulley tilt, the pulley's diameter and the belt's length. Considering the same system parameters the angled pulley shows a higher efficiency than the skewed pulley.

The quality of a belt tracking system depends, among other things on the relationship between efficiency and induced belt stresses. A quality parameter for the skewed pulley and the angled pulley can be derived: Angling and skewing of a cylindrical pulley leads to the same quality factor. Comparison between the numeric solution and measurements performed at a test bench show a good accordance.

With a view to minimising belt stresses combined with adequate tracking effects, optimised pulley kinematics as well as optimized pulley tilts can be found by using flat belt mechanics.

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