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Determination of the effect of temperature and relative humidity on the friction coefficient of V-belt mechanism

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In the V-belt drive system, temperature and humidity are the most effective parameters affecting the slippage. This study is done in two stages. Firstly, experimental study has been carried out and the effect of temperature, relative humidity on the slippage between V-belt and pulley has been analyzed. At the second stage, non-linear regression analysis has been carried out to get a prediction equation for determining of friction coefficient between V-belt and pulley at the different temperature and humidity. In the analysis MATLAB Statistics Toolbox was used. At the result of the analysis the prediction equation has been obtained with 0.995 correlation coefficient. It has been seen that increase of temperature and humidity leads to decrease in the coefficient of friction (slippage raises). In high humidity conditions, slip quantity raises rapidly when temperature is 60-80°C.

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V-belts consist of fiber reinforced elastomer matrix. Hence, these have only tension rigidity without any compression, bending and torsion rigidity. For a long time, V-belts have been used as a power transmission mechanism. During torque transmission slippage occurs between belt and pulley, which depends on friction coefficient and the belt deformation during the wrapping and unwrapping. Hence, the slippage affects efficiency of mechanism. In the V-belt drive system; the amount of slippage varies in respect to environmental conditions and system parameters[1]. In the literature, there are many studies discussing the slippage. Gebert[1] and Chen *et al.*[2] investigated the slip factor in the V-belt pulley system. V-belt drive system has four main parameters that affect belt slip, i.e., elastic creep along the belt, shear deflection that varies both in axial and radial directions, flexural rigidity on the input and output of pulley and compliance in the radial direction[2]. Gebert[3] proposed that the slippage should be considered as a calculation factor of speed loss. Moreover, it should be participated in the design of the mechanism. Peeken and Fischer[4] carried out a study on the torque transmission of the belt, which was statically tightened and the effect of the temperature on the power loss was discussed but its effect was less explained. Gebert[5] investigated the effect of pre-tension forces on the power loss and defined optimum pre-tension forces on the V-belt.

Dalgarmo *et al.*[6] explained that the mechanism of the belt noise generated from tangential slip is harmonic excitation of the fundamental vibration mode of the belt. Fujii *et al.*[7] discussed the mechanism of the lateral vibration of belt. Alciatore and Traver[8] investigated two theories of belt mechanics. In their study, it is pointed out that the coefficient of friction is mainly affected by many parameters such as temperature, slip, speed, humidity and material behaviour.

It is seen in the literature, there are two main factors discussing about the efficiency of V-belt pulley mechanism. One is mechanical and constructive structure of the mechanism. Other is environmental conditions such as temperature, humidity and abrasive particles. But the temperature and humidity are the most effective. In the published articles and manufacturer catalogs, some empirical data are available for many standardized V-belt types. These data provide information, which allow a designer to select a belt for application. However, these data are not enough to determine the efficiency of the system, since it does not contain any information about the effect of the environmental conditions, such as humidity and temperature. These conditions are very important for the special applications such as textile industry, the cement

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manufacturing industry driving of agricultural machine at the open air. Thus, in this study, a prediction equation to determine the effect of humidity and temperature on the slippage and the changing of coefficient of friction between belt and pulley is derived.

Theoretical Background

In the literature[6,8,9], the ratio of slippage in belt/pulley mechanisms is defined as,

$$s = \frac{\Delta\omega}{\omega_{dr}} \qquad \dots (1)$$

where $\Delta\omega$ indicates the difference of angular velocity between driver and driven pulleys and ω_{dr} denotes angular velocity of the driver pulley. In accordance to revolution of pulley this equation can be rearranged as follows;

$$s = 1 - \frac{n_{dn}}{n_{dr}} \qquad \dots (2)$$

where n_{dn} is speed of driven pulley; n_{dr} is that of driver pulley. On the other hand slip ratio has been determined theoretically[1,3] and depending on the many parameters,

$$s\frac{c}{F_1+F_2} = \left[1 + c_0\left(\frac{1-\mu\tan\beta}{\tan\beta+\mu} + k_0\right)\right]\lambda \qquad \dots (3)$$

This equation defines slip factor in V-belt pulley mechanisms in terms of geometrical structure of belt and pulley, and mechanical properties of the belt.

Where λ is coefficient of traction that is defined earlier[1] as,

$$\lambda = (F_2 - F_1)/(F_2 + F_1) \qquad \dots (4)$$

If Eq. (4) is substituted in Eq. (3) the slip factor can be written as,

$$s = \left[1 + c_0\left(\frac{1-\mu\tan\beta}{\tan\beta+\mu} + k_0\right)\right]\frac{(F_2 - F_1)}{c} \qquad \dots (5)$$

Substituting parameters of the belt into Eq. (5), slip factor can be obtained on the normal atmospheric condition. The parameters belongs to 13×1425 DIN 2215 type V-belt obtained from experiment and manufacturer catalogues as: (i) longitudinal stiffness of V belt, c= 75 kN, ($c=F/\varepsilon$ where F is axial force and ε is axial strain of belt), (ii) radial spring constant depending on axial pressure, k_1=31 N/mm^2 (k_1= 4 tanβ EH/B), (iii) modulus of elasticity, E=38 N/mm^2, (iv) longitudinal spring constant (dimensionless), c_0 = 0.55, (v) radial spring constant (dimensionless), $k_0 = k_{02} + k_{03}$ = -0.45, (vi) radial spring constant depending on radial pressure (dimensionless), k_{02}= -0.67, (vii) wedge angle, β=18° , (viii) pitch radius of the driver and driven pulleys, R= 66 mm, (ix) pitch width V belt, B= 11 mm, (x) Poisson ratio, ν=0.5 [$\nu = (\Delta B/B)/(\Delta L/L)$] according to reference[1], (xi) difference between tight side tension and slack side tension, (F_2-F_1)=373 N and (xii) coefficient of friction, μ = 0.4

According to V-belt parameters, the longitudinal spring constant c_0, can be calculated as[1,3],

$$c_0 = c/R^2 k_1 \qquad \dots (6)$$

Non-dimensional radial spring constant depending on radial pressure, k_{02} can be calculated[1],

$$k_{02} = k_1/k_2 \qquad \dots (7)$$

where k_2 = 46 N/mm^2, radial spring constant depending on radial pressure were obtained experimentally. Non-dimensional radial spring constant depending on belt force, k_{03} can be calculated as defined in earlier[1,3].

$$k_{03} = \nu B_0/2c_0\tan\beta \qquad \dots (8)$$

where $B_0 = B/R$ =non-dimensional belt width. Non-dimensional radial spring constant $k_0 = k_{02} + k_{03}$, can be calculated as,

$$k_0 = k_{02} + \frac{\nu B_0}{2c_0\tan\beta} \qquad \dots (9)$$

Using above parameters in Eq. (5) the slip factor can be calculated without the effect of the temperature and relative humidity. The changes in slippage in V-belt mechanisms not only depend on the parameter listed above but also depend on the environment conditions. Hence, the effect of the temperature and relative humidity on the slippage obtained from experiment should be introduced in Eq. (5).

Experimental Study

In the experimental study, the slip quantity has been measured. The measurement procedure was based on determining the difference of rotational displacement between driver and driven pulleys. The pulleys and V-belt kept in an isolated cabin. Artificial environmental conditions were provided in the cabin by change of temperature and relative humidity

13×1425 DIN 2215 type V-belt and 13×140 V-pulley with wedge angle β=18° have been used. Driven pulley attached on a hydraulic dynamometer was driven by driver pulley. Driver pulley has been powered by an a.c. motor, which has 5 kW power and 1000 rev/min speed capacity. 25 Nm torque was supplied at 1000 rev/min speed by adjusting the liquid oil volume of dynamometer. Constant belt tension has been provided by hanging W = 262 N weights on the end of the tensioned rope as shown in Fig. 1.

Two electrical resistance wires (heat producer) with 800 W capacity were used to adjust the inside temperature of cabin. On the other hand, as seen in Fig. 1, pipelines that produce humidity were connected to the cabin from two different points to generate and adjust the relative humidity in the cabin. Model 8711 Thermo-Hygrometer was used to measure and adjust temperature and relative humidity of the cabin. At the beginning, temperature and humidity were measured at different points of the cabin. It was seen that temperature and humidity were homogenous due to the circulation effect of V-belt and pulleys. Hence, a thermo-hygrometer was placed inside of the cabin.

Two rotary encoders (Koyo Electronics TRD-J500-RZ type and 500 pulse/rev) were attached on the driver and driven pulleys. Data obtained from rotary encoders were transferred to the Data Acquisition Card via National Instrument CB-68LP model I/O interfaced. DAQ card was National Instrument Multifunctional, E serial and PCI 6024 model. Then the data transferred to the DAQ card were recorded on a PC.

A number of experiments have been carried out to define difference in revolution between drivers and driven shafts. During these studies, the system was run without torque transmission. The system has been run in two directions, i.e., the clockwise and the counter-clockwise. The rotational difference obtained from these studies was utilized for the calibration of the system, in order to see the effects of ambient conditions. Then, the system was run with a torque of 25 Nm, under standard atmospheric condition (20°C and 65% humidity). Thus, the amount of slippage under this condition has been found as a 3.49 degree/rev. This slippage is caused from several parameters such as elastical slippage of the belt, change of mean contact diameters of the pulleys during operation and coefficient of the friction between surfaces. If it is assumed that the belt and the pulleys do not wear, this figure will be constant as long as produced torque and revolution (rpm) do not change.

Results and Discussion

The belt and pulleys were located in an isolated space where artificial operating conditions in terms of temperature and relative humidity were formed. During the experimental study, relative humidity was changed between 35% and 95% with 10% steps while temperature was kept constant at 20°C, 30°C, 40°C,

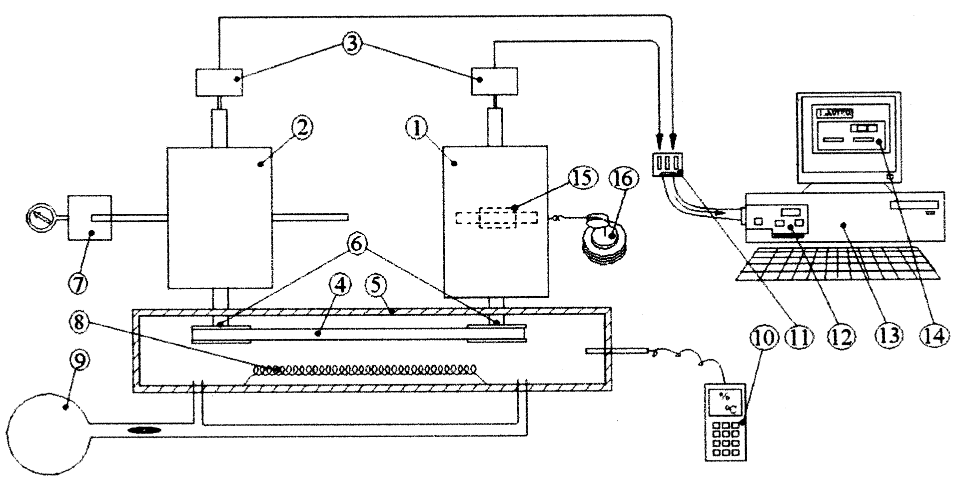

Fig. 1—Schematic view of the experimental set-up [1-Electric motor (a.c.), 2-Hydraulic dynamometer, 3-Rotary encoders, 4-V-Belt, 5-Isolated cabin, 6-V-Pulleys, 7-Force transducer, 8-Heater, 9-Humidity producer, 10-Thermo-hygrometer, 11-I/O Interface, 12-DAQ card, 13-PC, 14-DAQ software, 15-Axial rolling bearing, and 16-Constant tightness mechanism]

50°C, 60°C, 70°C and 80°C. The results were examined in two different ways, i.e., (i) to see the rotational difference at the different temperature under constant humidity, and (ii) to see the rotational difference at the different humidity under constant temperature.

Data obtained from experiments were transformed to slip quantity (s_q) between two pulleys and V-belt using following equation,

$$s_q=\theta_{dr}-\theta_{dn} \quad \ldots (10)$$

where, θ_{dr} is rotational displacement of driver pulley and θ_{dn} is rotational displacement of driven pulley.

The effects of the relative humidity and temperature on the slip quantities are given in Table 1. Table 1 consists of the sum of two slip quantities. One of them is result from mechanical effects the other one is result from relative humidity and temperature. The slips quantities result from mechanical effects were determined at the beginning of the experiment as a 3.49 degree/rev. On the other hand it was approved from Eq. (5).

As seen from Table 1, an increase in slip quantity under temperature of 20-40°C with relative humidity of 35%, 45%, 55%, 65% and 75% are 0.07 degree and 0.08 degree. An increase in slip quantities between 40°C and 60°C are higher than the ones between 20°C and 40°C. However, an increase in slip quantities between 60°C and 80°C are quite much and are respectively 0.27, 0.71 and 1.46 degrees. This originates from the facts that the belt does not contact with the surface of the pulley uniformly, since belt gets soft and high amounts of water vapour occurs between the belt and pulley due to elevated relative humidity. This is caused by humidity content of air per unit volume, which gets a higher with an increased temperature. This originates from the fact that air at a high temperature requires a higher amount of humidity than the amount to be contained by air at a lower temperature for the same relative humidity[10]. This reality causes an increase in elastomer friction and boundary friction in V-belt mechanisms at elevated temperature and relative humidity[11].

On the other hand, an increase in slip quantities under temperature between 20°C and 40°C at the relative humidity of 85% and 95% are quite low and are 0.01 and 0.09 degree/rev. However, slip quantities under temperature between 60°C and 80°C get higher by reducing with 0.22 and 0.3 degree/rev. An increase in slip quantities under temperature between 40°C and 80°C are higher and steeper than the above-mentioned figures. They are respectively 0.22, 0.3, 0.43, 0.82 and 0.9 degree/rev. Consequently, it can be stated that slip quantities under low relative humidity and low temperature condition increase slightly, while those at high relative humidity and high temperature conditions increase dramatically.

In this study, the slip factors were calculated in Eq. (2) using data obtained from experimental study in various humidity and thermal conditions is shown in Table 2.

It is seen form the experimental study that the slip between V-belt and pulley is affected due to relative humidity and temperature. The relative humidity may show lubrication effect on slippage on the other hand the temperature affects the V-belt's stiffness. Combination of these two effects on the slippage may be assumed that the friction coefficient between belt and pulley changes. Hence, the slip factors that affected from relative humidity and temperature can be calculated using data obtained from experiment. Then the affected friction coefficient from relative humidity and temperature is calculated using Eq. (5). The normal friction coefficient between V-belt and pulley has given as μ_n =0.4 by V-belt manufacturer with Ra =0.8 μm of pulley surface roughness. In this study the pulley surface roughness was also Ra =0.8 μm. The affection quantities of the relative humidity

Table 1—The effects of the relative humidity and temperature on the slip quantities Δθ (degree/rev.), for per revolution of driven pulley

Temperature, °C	Relative humidity, %						
	35	45	55	65	75	85	95
20	3.44	3.47	3.48	3.49	3.51	3.52	3.53
30	3.59	3.62	3.64	3.65	3.67	3.69	3.78
40	3.78	3.78	3.79	3.83	3.86	3.95	4.17
50	3.98	4.14	4.22	4.26	4.29	4.36	4.66
60	4.41	4.43	4.48	4.55	4.69	4.92	5.49
70	5.13	5.16	5.31	5.38	5.59	5.84	6.66
80	6.05	6.25	6.75	6.93	7.02	7.51	8.31

Table 2— Slip factors depending on the change of relative humidity and temperature for per revolution of driven pulley

Temperature, °C	Relative humidity, % 35	45	55	65	75	85	95
20	0.009581	0.009647	0.009678	0.009714	0.00975	0.009789	0.009808
30	0.009978	0.010064	0.010111	0.010142	0.010211	0.010253	0.010519
40	0.010514	0.010519	0.010531	0.010658	0.010733	0.010981	0.0116
50	0.011061	0.011511	0.011733	0.011847	0.011936	0.012117	0.012947
60	0.012269	0.012319	0.012444	0.012644	0.013031	0.013678	0.015261
70	0.014253	0.014344	0.014769	0.01495	0.015528	0.016239	0.018508
80	0.016806	0.017353	0.018744	0.019244	0.019492	0.020875	0.023092

Table 3—The affected friction coefficient from relative humidity and temperature

Temp., °C	Relative humidity, % 35	45	55	65	75	85	95
20	0.408	0.406	0.402	0.400	0.397	0.393	0.392
30	0.382	0.376	0.374	0.372	0.368	0.366	0.352
40	0.352	0.352	0.351	0.345	0.341	0.329	0.303
50	0.326	0.307	0.298	0.293	0.290	0.284	0.257
60	0.278	0.277	0.273	0.266	0.254	0.237	0.201
70	0.223	0.220	0.211	0.207	0.196	0.183	0.150
80	0.174	0.166	0.147	0.142	0.139	0.125	0.106

and temperature on the friction coefficient between V-belt and pulley are shown in Table 3.

In order to determine the change of friction coefficient with relative humidity and temperature (in the range of 20°C-80°C temperatures and 35%-95% relative humidity) a non-linear regression analysis was conducted utilizing experimental results presented in Table 2. Thus, an equation predicting coefficient of friction in terms of relative humidity and temperature was developed with a correlation coefficient 0.995. The equation is,

$$\mu_a = \mu_n + 0.0455 + 0.183\,T - 0.358M - 0.1745\,T^{1.014} + 0.365M^{0.996} \quad \ldots (11)$$

where μ_a is the affected friction coefficient, μ_n is the normal friction coefficient at the 20°C and 65% humidity condition. T is temperature (°C) and M is relative humidity (%).

The calculated value depending on the prediction model for the friction coefficient of the V-belt system versus the experimental ones are shown in Fig. 2. To measure the accuracy of the prediction model, graph is provided with a straight line indicating the perfect prediction and a ±10% error band.

The predicted friction coefficient as a function of the experimental value is shown in Fig. 2. The predictions for the friction coefficient yield a mean relative error (MRE) of 2.87%, a root mean square error (RMSE) of 0.01 and a correlation coefficient of 0.995 with the experimental data.

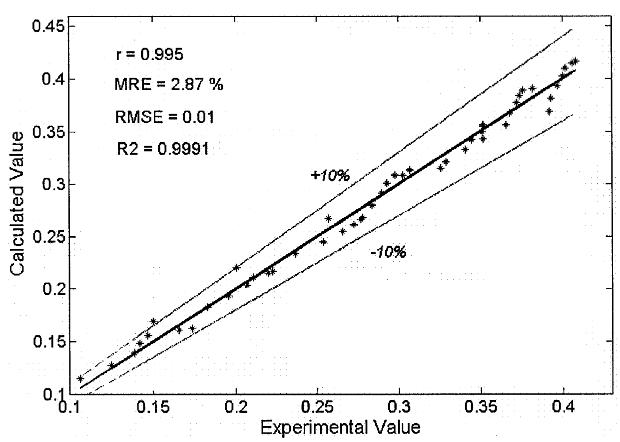

Fig. 2—The plot between calculated and experimental values of friction coefficient

The mean relative error (MRE) was calculated according to Eq. (12),

$$\mathrm{MRE}(\%) = \frac{1}{N}\sum_{i=1}^{N}\left|100\frac{(a_i - p_i)}{a_i}\right| \quad \ldots (12)$$

Finally, the root mean square error (RMSE) was also used to show the performance of the prediction. RMSE is a statistical measure of the magnitude of a varying quantity expressed by

$$\mathrm{RMSE}=\sqrt{\frac{1}{N}\sum_{\mathrm{i}=1}^{\mathrm{N}}(a_{\mathrm{i}}-p_{\mathrm{i}})^{2}} \quad \ldots (13)$$

Because the correlation coefficient is 0.995, it can be stated that the predicting equation works properly. According to Eq. (11) at T = 20°C and M = 60% the coefficient of friction between V-belt and pulley μ_a is nearly equal μ_n. On the other hand, using the affected friction coefficients, depending on the temperature and relative humidity, are shown in Table 3. This means that it is easy to find the effect of temperature and relative humidity on the friction coefficient and slip factor in the Eq. (11).

Conclusions

If the environmental conditions surrounding the V-belt mechanisms are not normal, it is required to determine the slippage of the mechanism for the related operating conditions and design the mechanism accordingly. Therefore, slippages in the mechanism for various environmental conditions have been determined experimentally and analyzed. Utilizing the experimental data, a prediction equation defining the effect of temperature and relative humidity on the coefficient of friction between the belt and pulley has been developed. Using this method the natural friction coefficient between V-belt and pulley can easily be calculated when temperature and relative humidity are given. This helps the construction of the system working under specified conditions.

Nomenclature

$B(B_0=B/R)$ = pitch width of the belt
E = modulus of elasticity
F_1 = belt force on the slack side
F_2 = belt force on the tight side
H = belt thickness
M = relative humidity
R = pitch radius of the driver and driven pulleys
T = temperature
c = longitudinal stiffness ($c=F/\varepsilon$ where F is axial force, ε is axial strain of belt)
c_0 = longitudinal spring constant ($c_0=c/R^2k_1$, dimensionless)
$k(k_0=k_{02}+k_{03})$ = radial spring constant (dimensionless),
k_1 = radial spring constant depending on axial pressure, (k_1=4 tanβ EH/B)
$k_2(k_{02}=k_1/k_2)$ = radial spring constant depending on radial pressure (dimensionless)
k_3 = radial spring constant depending on belt force (dimensionless)
n_{dr} = driver pulley velocity (rpm)
n_{dn} = driven pulley velocity (rpm)
s = slip factor
β = wedge angle,
λ = traction coefficient
μ = friction coefficient,
μ_a = affected friction coefficient
μ_n = normal friction coefficient
ν = poisson ratio,
ω = angular velocity
$\Delta\omega$ = angular velocity difference between driver pulley and driven pulley

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