Evaluation of a test setup to measure friction damping

Citation for published version (APA):

Document status and date:
Published: 01/01/2005

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Download date: 25. Apr. 2019
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DCT 2005.81

Traineeship report

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Eindhoven, June, 2005
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1. Introduction

Friction is often seen as a problem because of unwanted vibrations, wear, etc. Friction however could also be useful at certain moments for example in noise reduction. That’s why there has been a study which resulted in the paper: ‘Energy dissipation of a friction damper’ [1]. This paper describes an analytical solution for the dissipation of energy due to friction which depends on the system parameters. But it only consists of an analytical approach without an experimental validation.

Subsequently the objective for this assignment is to collect data to qualify the results found in the paper mentioned earlier. The problem is however that there isn’t a setup available to do the necessary measurements. That’s why there should be a new setup developed which approaches an ideal mass-system with adjustable friction to collect the data.

This report starts with an explanation of the analytical solutions for the energy dissipation in a friction damper. After that there will be a description of the development of the setup. Subsequently the measurements will be discussed. Finally there will be some suggestions to research later.
2. Theoretical Background

The theory behind this study uses the simplest model of a sliding block with the mass excited by an external force (figure 2.1.). For the friction between the block and the base surface a coulomb friction model is used with the same static and dynamic friction coefficients.

![Figure 2.1: Model of the mass with friction](image)

The way of movement of the block is dependent of 4 parameters, namely: the amplitude (F) and the frequency ($\omega_0$) of the excitation, the mass of the block (m) and the friction force between the block and the surface ($F_f$). The external force acting on the block is equal to (1).

$$F_{\omega_0}(t) = F \sin(\omega_0 t)$$  \hspace{1cm} (1)

There are 3 possible motions for the block: stick, continuous sliding and stick-slip. The way of motion can be determined on the basis of the normalized friction force parameter $f_f$ as defined in (2).

$$\sin(\omega_0 t) = \pm \frac{F_f}{F} = \pm f_f$$  \hspace{1cm} (2)

The positive or negative sign in (2) corresponds to a negative or positive acceleration of the block. Stick occurs for $|f_f| \geq 1$, which implies that the friction force is greater than the excitation force. The mass won’t move and sticks to the floor at all times. When $|f_f| < 1$ there are two possible motions left, either the block is in continuous sliding or it is in stick-slip movement (figure 2.2.).

![Figure 2.2: Continuous sliding of the block with $f_f = 0.4$ (left) and stick-slip movement of the block with $f_f = 0.8$ (right)](image)

Now that the motion of the block is known, it is interesting to look at the energy dissipated every cycle. The energy dissipated is equal to the integral of the product of the dissipating force times the velocity of the block (3). Herein can the dissipated energy be normalized through (4).

$$E_d = \int_0^T F(t)v(t)dt$$  \hspace{1cm} (3)

$$e_d = \frac{E_d m\omega_0^2}{F^2}$$  \hspace{1cm} (4)

Now there is an expression for the normalized dissipated energy, this energy can be plotted as a function of the normalized friction to find a maximum (figure 2.3.).
It is trivial that $e_d$ equals zero for both $f_f$ of zero and one. There is namely no energy dissipated when there is no friction ($f_f$ equals zero) or when the block isn’t moving ($f_f$ equals one). In between there lies a maximum which can be an interesting design parameter.

The goal of this project is to build a test setup which will behave like the system in figure 2.1. and try to find a relationship between excitation amplitude and energy dissipation similar to figure 2.3.
3. The test setup

To check the theory stated in the previous chapter it is important to have a setup which would act as an ideal mass-system with friction in which this friction is adjustable. By this it could be possible to analyze the friction and the behavior of the moving mass.

3.1. Initial setup

At first the setup was a metal slide that moved through 2 parallel linear bearings. Extra friction could be added by a lightweight screw, mounted on top of the front end of the slide. By tightening the screw, the friction between it and the fixed world would increase. Of course there is also some friction between the slide and its bearings. This however can be reduced to a minimum by adjusting these bearings properly and clean them, so that the friction that comes from the screw is significantly larger. The desired movement is transferred to the slide by a shaker which is connected by a rod. The force applied to the slide by the shaker is measured by a force cell. The resulting velocity and acceleration of the slide are measured by a laser (vibrometer) respectively an acceleration cell.

3.2. Second setup

It turned out that at the turning points of the movement the bending of the screw became an issue. At those points the screw bend back the other way which resulted in a discontinuity in the displacement. To avoid this problem, a metal screw instead of the lightweight screw (higher E-modulus) was used. Furthermore a piece of hard metal was added, so that the point where the screw touched the fixed world was almost on the line of displacement, so there would be no significant bending anymore. For this elevation is specific chosen for a piece of hard metal, because it has the advantage that the friction will be smoother. Moreover is a metal piece used to fix the screw to the slide, to avoid the problem that the line of displacement isn’t parallel to the contact surface. The metal piece will act as a spring, as a result of what the tip of the screw can follow the contact surface and keep the force constant. This setup is shown in figure 3.1. and its characteristics are found in figure 3.2.

Figure 3.1. : Overview of the second setup. 1) Shaker, 2) rod, 3) clamp to fix the setup to the table, 4) linear bearing, 5) assembly bar for the leaf spring, 6) screw for adding friction, 7) elevated piece of hard metal
3.3. Final setup

After these last adjustments it turned out that there were still some things to adjust to get an as ideal setup as possible.

The screw together with its assembly caused some unwanted extra dynamics. Because of this there appeared a few resonance peaks in the magnitude plot around the 140 Hz (figure 3.2.). The solution for this problem was to replace the screw with a leaf spring through which the extra dynamics disappeared out of the system.

The assembly bar for the leaf spring induced in his turn also some extra friction. The fixation of this bar to the metal slide is over determined. Therefore it bended the plate if the bolts were tightened. This bending made the slide ran into the bearings which caused the extra friction. Because of this the bar was replaced by a clamp.

The lowest own frequency left in the system (figure 3.2.) around the 1200 Hz is caused by the rod connecting the shaker to the slide. This can’t be removed from the system, but after adding some damping in the form of a casing, the influence is reduced.

Another problem was that the bearings loosened after some time. This came from the way the entire setup was fixed to the table. It was namely fixed using four clamps; consequently it was over determined again. To solve this, the complete setup was fixed to a thick metal plate which in his turn was fixed to the table, using three clamps to avoid over determination.

After all these adjustments the moving mass acted almost as an ideal mass for frequencies above the 8 Hz (figure 3.3). For lower frequencies however there seems to be a sort of stiffness in the system. It turned out that this stiffness comes partly from the shaker (figure 3.4.). This shaker however couldn’t be replaced, so this stiffness should be taken into consideration. Especially because these low frequencies are in the range of interest for the upcoming measurements. These low frequencies are interesting, because for these frequencies there is a larger amplitude range, which results in a less sensitive response for small amplitude changes. Through which the response of the system can be analyzed more exactly.

The final setup with which the measurements were done is shown in figure 3.5.
Figure 3.3: Bode plots for the transfer function (force-acceleration) for the most ideal setup.

Figure 3.4: Bode plots for the transfer function (force-acceleration) of the second setup with and without the shaker attached (notice that this figure is made before the adjustments mentioned in ‘final setup’).

Figure 3.5: Overview of the final setup. 1) rod with casing, 2) force cell, 3) acceleration cell, 4) leaf spring.
4. Measurement Results

4.1. The Measurements

Because a large amount of measurements were required, use has been made of Siglab in combination with Matlab (Appendix 1) to automate the measurements. Data has been collected for two different excitation frequencies, namely 8 and 12 Hz. For every frequency four datasets have been collected, consisting of two datasets with low starting amplitude and ending with high amplitude (Up 1,2) and two datasets the other way around (Down 1,2). So there are 8 datasets collected in total. The first thing to control is to check whether those measurements are repeatable or not. This is done by comparing them to each other (figure 4.1.).

![Figure 4.1. Control for repeatability for a measurement of 8 Hz with 0.4V (left) and 12 Hz with 0.4V (right)](image)

It is clear that the measurements with a 12 Hz frequency are far more repeatable than the 8 Hz measurements, in spite of there is a negligible difference between the ‘up’ and ‘down’ datasets. But more important, the measurements of 12 Hz look like the expected behavior as stated in figure 2.2. whereas the 8 Hz measurements aren’t as ideal. Because of that, the rest of this chapter will depend on the 12 Hz measurements. The reason why the 8 Hz measurements aren’t repeatable and doesn’t look like the expected behavior isn’t clear, but it may be a result of the fact that the system doesn’t behave like a mass for lower frequencies.

4.2. Stick-slip and continuous sliding

The next step in these analyses is to check whether the predicted behavior of the block (chapter 2) matches the reality. As stated before this behavior depends on the normalized friction factor $f_f$. In our measurements both the friction and the frequency aren’t changed, so the only factor that influences $f_f$ is the amplitude of the excitation, wherefore applies that increasing amplitude causes $f_f$ to decrease. As can be seen in figure 4.2. this behavior can be found in our setup although with some abnormalities. So is for example very clear from both figures that the behavior isn’t symmetric as expected. For stick-slip movement the only stick is observable during increasing speed. The same phenomena can be found in the continuous sliding figure, where you can only find the specific kink during increasing speed. An explanation for the fact that the velocity response for this system isn’t symmetric as expected, could be that the friction isn’t equal to coulombs friction model as assumed. Another explanation could be that the applied force isn’t symmetric and sinusoidal as well, due to finite stiffness in the transmission from the shaker to the slide. In our setup it’s namely not the force that is prescribed, but the voltage over the shaker is.

Another abnormality is the average value, these aren’t equal to zero for both measurements as expected, but lies around the 0.002 m/s and is approximately constant over the entire measurement range. This is probably caused by an offset in the output channel.

For all calculations the average value is taken into account, for all figures however, the measured data is used.
4.3. Dissipated Energy

In spite of the fact that the time-behavior of the setup doesn’t match the expected behavior exactly, it approaches it quite good. That’s why there is also tried to check the dependency of the normalized dissipated energy as a function of the normalized friction parameter. Actually it is plotted as a function of the output voltage (figure 4.3.) (Appendix 2), which is indirect associated with the normalized friction parameter. A relationship needs to be found between input voltage and the friction parameter (2) in order to compare the calculated figures in the next paragraph with the predicted figures from chapter 2.

To calculate the dissipated energy all measured data is corrected for its offset. To normalize the dissipated energy, the mass must be known. This mass can be found with the transfer function from force to acceleration (figure 3.3.) through (5).

\[
\frac{dB}{dBm} = 20 \log \left( \frac{1}{m} \right)
\]  

(5)

For this system it comes down to a mass of 0.14 kg.

As formula (4) shows, the dissipated energy is normalized using the amplitude of the excitation force. That’s why that parameter is also used in figure 4.3. to normalize the energy, knowing that the excitation force isn’t harmonic as demanded in the theory.
As you can see the figure doesn’t show one maximum as predicted, but two maximums. If you study the used data some more it appeared that the amplitude of the force didn’t increase over the entire range when the input voltage increased as you would expect (figure 4.4.). As you can see the amplitude falters around the 0.3 V, just the area where the second peak in the dissipated energy figure appeared. Another remarkable thing is that around the same input variables the mean value of the force makes an unusual step (figure 4.5.). This step isn’t noticeable in the datasets of the voltage, speed and acceleration.

Because these phenomena couldn’t be explained, a second order fit has been used to approach a more logical response for the amplitude of the force. And when this fit in his turn is used to determine the normalized dissipated energy (figure 4.3.), you’ll find one maximum in the curve as expected. For both figures applies that the order of magnitude of the normalized dissipation energy is the same as predicted in theory.

Figure 4.3. : Normalized dissipated energy as a function of the input voltage; calculated using the measured amplitude of the force (left) and calculated using an fit of the amplitude of the force (right)

Figure 4.4. : Amplitude of the force as function of the input voltage as measured and fitted data

Figure 4.5. : Mean value of the force as function of the input voltage
The results are nevertheless questionable knowing that the excitation force isn’t harmonic as demanded in theory and the choice for the second order fit isn’t argued properly. That’s why there is also looked at another way to normalize the dissipated energy. This can for example be done using the amplitude of the input voltage as parameter (figure 4.6.). The input voltage is namely harmonic by definition, because it is prescribed.

As you can see, the figure shows again a sort of lump as expected, but it is very distorted. The maximum lies around an input voltage of 0.05 V. From this appears that there are few measurements done in the stick-slip region.

### 4.4. Behaviour changeovers

It becomes also clear that there are few measurements done in the area of interest when you look at the velocity-time plots of the different input voltages. There are namely very little measurements done for stick-slip, while there are a lot of continuous sliding measurements. A dataset for example consists of 71 measurements, of which approximately only six measurements (0.03V – 0.08V) are in the stick-slip behavior (figure 4.7.) while there are sixty-two measurements (0.09V – 0.70V) done for continuous sliding (figure 4.8). For the lowest three measurements (0.00V – 0.02V) it is a matter of presliding (figure 4.9.).
The changeover between stick-slip and continuous sliding can be seen best in the time-acceleration plots. For continuous sliding there is namely no caving to zero as strong as can be seen in the acceleration plot for stick-slip although there is some caving. The exact point of changeover is hard to determine, because the differences aren’t that big around the changeover.

When you look at what behavior occurs when the normalized dissipated energy finds it maximum, you find out that this is stick-slip movement if you normalize with the input voltage (0.05V) or continuous sliding, close to stick-slip movement if you normalize with the amplitude of the excitation force (+0.15V).

This fact can be used to choose the best normalize parameter for this moment. The theory namely predicts a maximum in the energy dissipation for an $f_f$ of 0.45 (6) and the changeover between continuous sliding and stick-slip for an $f_f$ of 0.53 (6). So the theory predicts that the maximum in energy dissipation occurs in the continuous sliding region close to stick-slip behavior. If you assume that the theory is right, you should then normalize the dissipated energy with the amplitude of the force instead of the amplitude of the input voltage.

$$f_{f_{\text{max}}} = \frac{\sqrt{2}}{\pi} \approx 0.45$$

$$f_{f_{\text{th}}} = \frac{1}{\sqrt{1 + \frac{\pi^2}{4}}} = 0.53$$

(6)

Figure 4.9.: Time-velocity plots for presliding (left) and stick-slip (right)

If you take a closer look at the smallest excitation amplitudes, it can be noticed that for 0.03V and 0.04V there is also stick observable during decreasing speed. This however isn’t very clear because the velocities for these low voltages are nearly as small as the system noise for presliding (figure 4.9.). For very low amplitudes applies namely that the finite stiffness through which the friction is connected to the mass becomes (figure 4.10.) more important. Therefore, below 0.03 V, the presliding behavior of the mass is measured. This behavior however isn’t included in the model presented in chapter 2.

Figure 4.10.: Model of the mass with the friction connected with a finite stiffness
5. Conclusions

- A test setup has been built which is able to satisfy the theory of a moving mass with friction as good as possible. This setup is used to measure energy dissipation through friction.
- The first measurements give promising results. A changeover between stick-slip and continuous sliding can be found. Moreover energy dissipation is determined and compared to theory.
- The setup however still needs to be improved, because:
  - However two different frequencies are measured; only the 12 Hz measurements were useful, because the behavior of the 8 Hz measurements were far from the ideal as stated in the theory. Because of this it wasn’t possible to check whether the maximum in the dissipated energy curve comes with same normalized friction parameter for different excitation frequencies.
  - The normalized energy dissipation is given as a function of the input voltage. In theory however it is given as a function of the normalized friction parameter, but as there is nothing known about the exact friction, it isn’t possible to lay a link between the input voltage and the normalized friction parameter.
6. Future Work

After these measurements there is still some work left that should be done. There are namely a couple of unsolved problems left which are very unsatisfactorily.

- There are too few measurements done in the area of interest, namely stick-slip behavior or around the maximum of the normalized dissipated energy. This however can be solved easily.
- It might be possible to get datasets for other frequencies than 12 Hz with the same setup. Because when you add some extra mass to the slide, the amplitude range will increase. As a result of what the response will be less sensitive to the same amplitude changes. Because of this also higher frequencies are analyzable, which they weren’t without extra mass, since the amplitude range wasn’t large enough.
- An additional advantage of the extra mass is that it will bring the resonance in the lower frequencies down. Because of this, also lower frequencies than 12 Hz will be analyzable. Adding mass is however bound to a maximum, because when you add too much mass, there will be too much friction in the bearings.
- An important thing is that you can’t control the system. In other words: you’re not able to let the slide follow a prescribed position, excite with a prescribed force or give the slide a prescribed velocity. If you’re able to do so, you can for example prescribe a harmonic force, to satisfy the theory stated in chapter 2 as a result of what you’re able to do more conscious assertions.
- An additional advantage of controlling your system is, that you can prescribe a triangular shape position signal, which will cause an intermittent positive and negative constant velocity. With this signal it would be easier to determine the velocity dependent friction force through which a relation might be found between the normalized friction parameter and the input voltage to compare figure 2.3. with 4.3.
7. References

8. Appendices

A.1. Automation of the measurements

clear all
close all
clc

vna_auto2('init'); %Initialize Siglab in the right mode
vna_setup_file = 'C:\My Documents\Thijs\Opstelling 3\autometing\Setup_File.vna'; %call on the right settings

for a = 1:191
    Ochan = 2;  %Determine the output channel for Siglab
    Freq  = 8;  %Determine the output frequency [Hz]
    dT    = 500;  %Determine the delay time [ms]
    Level = 0.1+(a-1)*0.01;  %Determine the start amplitude and the step size [V]
    siglab('Outsine',Ochan,Freq);  %pass on the information to Siglab
    siglab('OutLevel',Ochan,Level);
    siglab('DELAYms',dT);  %Let Siglab do the measurements
    SLm=VNA_AUTO2('meas2out',vna_setup_file,'new','output_file','SLm');
    Data.force(a,:)=SLm.scmeas(1).timea;  %Write the collected data in a structarray
    Data.velocity(a,:)=SLm.scmeas(2).timea;
    Data.acceleration(a,:)=SLm.scmeas(3).timea;
    Data.voltage(a,:)=SLm.scmeas(4).timea;
end

Data.time = SLm.tdxvec;

save('meas140405_12HzU1','Data')  %Save the collected data to the hard drive

siglab('OutLevel',Ochan,0);  %Stop the output
A.2. Calculating the normalized energy dissipation

clear all
clc
close all

m = 0.14;  % Determine the mass [kg]
f = 12*2*pi;  % Determine the frequency [rad/s]
n = 9;   % Determine the number of cycles

In = [];
Fv = [];
AmpF = [];

load meas140405_12HzU1.mat % Load the data

sized = size(Data.velocity);    % Determine the length of the dataset
dt = Data.time(2)-Data.time(1);  % Determine the step size in time
ne = round(n*(1/f)/dt);     % Determine the length of the needed dataset

for a = 1:sized(1)
    Fv = [Fv;Data.force(a,1:ne).*Data.velocity(a,1:ne)];  % Multiply Force by Velocity
    I = sum(Fv(a,:).*dt)/9;     % Determine the integral per cycle
    In = [In;I];

    maxF = max(Data.force(a,1:ne));
    minF = min(Data.force(a,1:ne));
    ampF = (abs(maxF)+abs(minF))/2;  % Determine the amplitude of the force
    AmpF = [AmpF;a,ampF];

end

[P,S] = polyfit(AmpF(:,1),AmpF(:,2),2);  % Fit the amplitude data

x = 1:71;
y = (P(1)*x.^2+P(2)*x+P(3))';  % Get the fitted data
x = 0:0.01:0.7;  % Determine the x-axis
E = m*f^2*In./(AmpF(:,2).^2);  % Compute the dissipated energy with the measured data
Ef = m*f^2*In../(y.^2);   % Compute the dissipated energy with the fitted data

figure  % plot the figures
plot(x,E,'r',x,Ef,'b')
grid on
xlabel('input voltage [V]')
ylabel('normalized dissipated energy [-]')