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ScienceDirect
Physics Procedia 70 (2015) 55 – 58
Physics Procedia

2015 International Congress on Ultrasonics, 2015 ICU Metz

# Ultrasonic friction reduction in Elastomer – Metal contacts and application to pneumatic actuators

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**Abstract**

Ultrasonic friction reduction is well known in metal-metal contacts. Due to the vibration, the stick phase in the contact phase vanishes and only sliding occurs. As long as the macroscopic relative velocity of the contact partners is much lower than vibration velocity, the necessary force to move the parts tends to (nearly) zero. If the effect also exists in material combinations with a significant difference in stiffness and damping characteristic has not been investigated in the past. This contribution shows the effect for various material combinations, which are typical for sealings in pneumatic actuators. Further, a novel integrated transducer design for a pneumatic actuator is presented. In this design the transducer also acts as moving part within the pneumatic actuator. The design challenges are the two contact areas on the moving part, where the friction reduction and consequently high vibration amplitudes are needed. The first area is fixed on the transducer geometry, the other is moving along the piston. This novel design has been implemented in the laboratory; detailed experimental results are presented in this contribution.


Peer-review under responsibility of the Scientific Committee of ICU 2015

*Keywords:* Ultrasonic Friction Reduction; Rubber-Metal Contact; Friction Control; Pneumatic Actuator; Ultrasonic Transducer Design

## 1. Introduction

Pneumatic actuators are used widely in industrial handling and automation applications. Usually pneumatic actuators are applied for positioning tasks. However, due to their non-smooth starting behavior, they are mostly switched from one end positions to another. There is a strong desire to apply pneumatic actuators for arbitrary

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Peer-review under responsibility of the Scientific Committee of ICU 2015
doi:10.1016/j.phpro.2015.08.040

position-time profiles. A smooth start is an essential need for this. Consequently, in the last years and decades researchers work on multiple approaches. Namely: (1) lubricants, (2) dither vibrations, (3) sealing materials, (4) sealing geometry, and (5) surface topology. All those approaches have a positive effect on the reduction of stick-slip behavior, but suffer from individual drawbacks. Therefore, a novel approach is very welcome.

The new idea presented here is the utilization of ultrasonic friction reduction. This technique was described by Pohlmann and Lehfeld [1]. The first applications have been for wire draw processes, here hard-hard contacts appear. Later Littmann et.al [2, 3] showed that the effect can be sufficiently modeled using Coulombs law. Further investigations followed e.g. by Kumar and Hutchings [4] or Teidelt et.al. [5]. One of the few applications with a hard-soft material combination was done by Bharadwaj et.al [6]. They used the effect to control the friction of safety belts in cars. A complete different application for the friction reduction in tillage has been studied by Kattenstroth et.al. [7,8] in the tool-soil contact. Gao et. al. [9,10] have studied the use of high frequency vibrations for friction reduction in parallel to our work. However, they use two completely different setups.

This contribution first presents the fundamental effect of ultrasonic friction reduction in rubber-metal contacts. Second the integration of an ultrasonic transducer into a pneumatic actuator is presented together with experimental results. The aim is to show the feasibility of the novel approach.

## 2. Preliminary Investigations on Rubber-Metal Contact

Two stepped bolted 20 kHz transducer have been setup to investigate two main configurations: Ultrasound induction on the moving side (rod setup) and on the fixed side (piston setup) with respect to the sealing. In the rod setup the contact position changes along the transducer, due to the actuator position. This leads to a location-dependent effect, Pham and Twiefel [11]. In the piston setup, the sealing is fixed on the transducer, consequently it is fixed on the vibration shape and the effect is basically independent of the actuators position. With a universal linear force-displacement test bench the friction behavior has been recorded, and analyzed. Fig. 1 shows the relative effect on the friction force, taking the situation without ultrasound as 100%. To drive the transducer, a digital PLL (DPC 500/100k) with current control [12] has been used. The transducer was operated in resonance. Therefor the current amplitude is proportional to vibration amplitude.

The exemplary results for a NBR70 O-Ring (ID 9mm, RD1.5mm) show clearly, that both the average friction (sliding) force as well as the breakaway force is significantly reduced. The effect on the rod configuration is smaller, due to the position influence. The maximum reduction has been obtained in the piston configuration with about 80%. The results show that a pneumatic actuator utilizing ultrasonic friction reduction is promising.

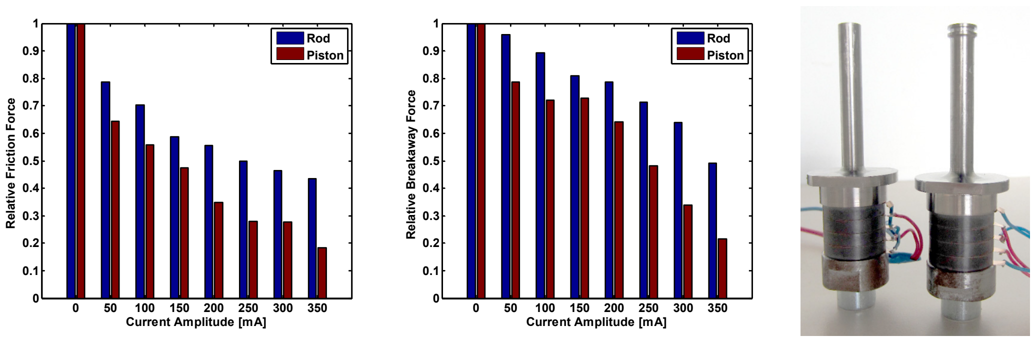


Fig. 1. (left) Relative Friction Force for different current amplitudes. (middle) Breakaway Force for different current amplitudes. (right) Transducer used, left "Rod" right "Piston".

## 3. Pneumatic Actuator with Integrated Ultrasonic Transducer

For a real pneumatic actuator much more demands needs to be fulfilled. As a minimum two seals are needed, one of them in piston and the other one in rod configuration. One of the big challenges is finding a design with sufficient vibration amplitudes that always reduces the friction at both seals. In Fig. 2 different concepts are sketched with the expected vibration shape indicated. Of these concepts only a) and d) allow to influence the friction on both seals simultaneously. Option a) looks advantageous due to the easy integration into the housing. However, here the bigger sealing is moving over the vibration shape. In summery option d) seems to be better.

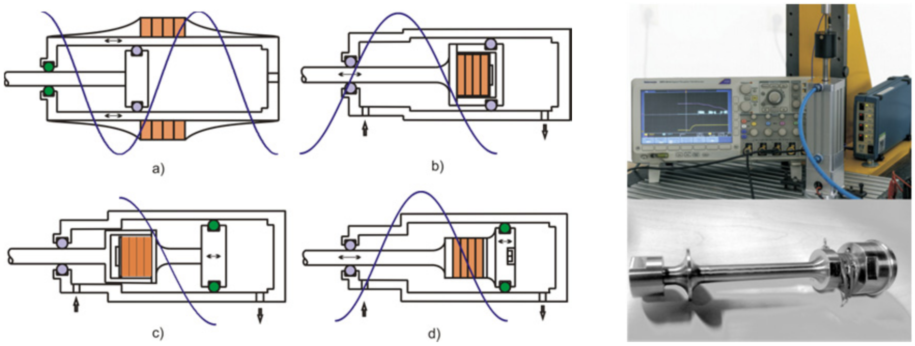


Fig. 2. (left) Concepts for integration of ultrasonic transducer in pneumatic actuators. (right bottom) Ultrasonic Piston. (right top) Universal Linear Force-Displacement Test Bench for Characterization.

Option d) was selected, knowing that the electrical connection will be challenging. The transducer was per-dimensioned utilizing a transfer matrix method approach [60]. The fine-tuning and optimization has been carried out utilizing the Ansys FEM Tool. The total length is 2 wavelengths, so that the rod seal's contact region is around an anti-node. The piston sealing is located on a further anti-node near the PZT. The "free" end has a step to decrease the length of the transducer. .The transducer is made of titanium and hart PZT (PIC181) and has its first longitudinal resonance frequency at 20 kHz. The seals are selected by standard criteria; the piston seal has the profile Z5, and the rod seal the profile EL.

Using the test bench, shown in Fig. 2, the characteristics of the pneumatic actuator is investigated. The displacement of the piston is measured using a LVDT, the force by a strain gage based force washer, and the current using a current probe. The data is recorded by a DAQ-System. The transducer is again controlled by our DPC 500/100k utilizing its phase and current amplitude control. A linear amplifier is used to provide the power.

Fig. 3 gives a first impression on the time behavior at constant air preasure. As soon as the vibration is switched on, the slope of the position changes significantly, meaning that the velocity of the piston increases. Furthermore, the transients at constant current amplitudes are measured. The current amplitude at resonance is directly proportional to the vibration amplitude of the transducer. The measurements clearly show the influence of the ultrasonic vibration. For the applied (small) air pressure, the time of travel has decreased by the factor 4.

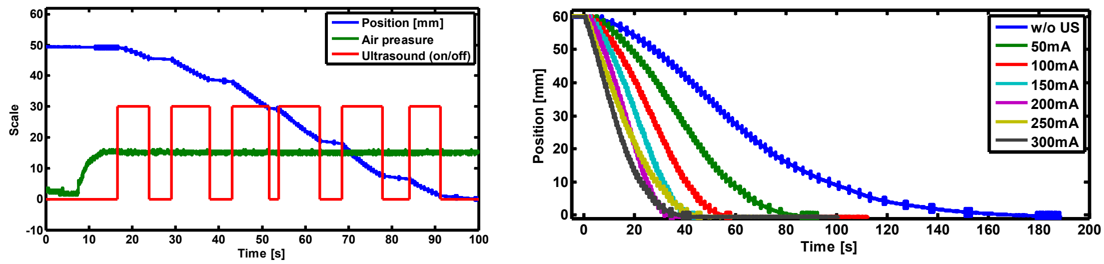


Fig. 3. (left) Transient behavior of novel ultrasonic pneumatic actuator. 0.75 bar air pressure. (right) Variation of current amplitude.

The ratio between maximum vibration amplitude and driving current is about 40µm/A. The position of the maximum Amplitude is near to the piston seal. The amplitude in the contact region of the rod seal varies between 30%-50% (depending on the piston position). The force-position behavior was measured as well. The results in Fig. 4 show the typical performance for a pneumatic actuator. At very small position, a force maximum appears, the breakaway force, than the force reduces over the position until a steady value is reached. The experiments are performed multiple times to create similar contact situations on the friction partners. The analyses of the measurements show the significant effect on the friction force. For this evaluation the breakaway force without ultrasound is the 100% basis. As in the preliminary experiments higher current amplitudes lead to significant less friction force.

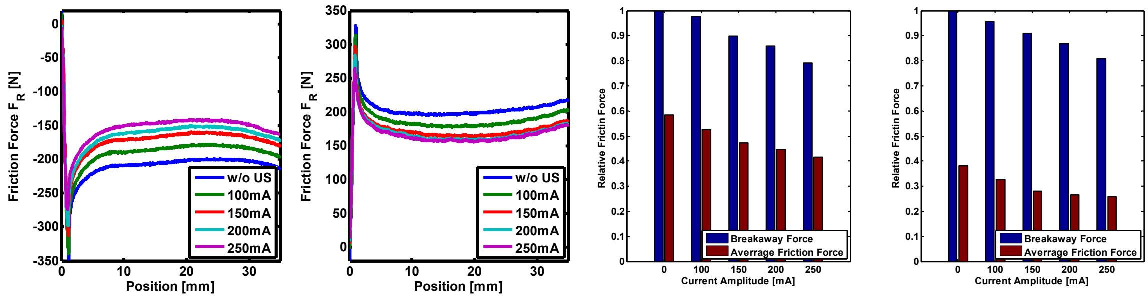


Fig. 4. (left ) Force-Position diagram for contracting actuator. (middle left) Force-Position diagram for expanding actuator. (middle right) Relative Friction force for expanding actuator. (right) Relative Friction force for contracting actuator.

## 4. Conclusions

Nowadays, pneumatic actuators suffer from a non smooth starting characteristic. This contribution presents a new approach reducing the breakaway forces, utilizing the ultrasonic friction reduction technology. This was formally used in metal-metal contacts only. In preliminary experiments it could be shown that the effect is applicable for elastomer-metal contacts also. Based on this, a new concept for pneumatic cylinders has been developed and characterized. The results show very promising and significant reduction of both the average friction force and the breakaway force. Summarizing, this work may be seen as proof of concept and justify further investigations.

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