Extended Performance of Hybrid Actuators[1]

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Abstract. A hybrid actuator basically consists of a piezoelectric and a magnetostrictive transducer oscillating in their resonant frequency. So the reactive energy is exchanged between both transducers, which leads to a high efficiency and a compact mechanical and electrical construction. Driven in its natural frequency, however, the strain-time characteristic of the hybrid actuator is always nearly sinusoidal; this restricts possible applications and therefore an extended performance was investigated by driving the actuator with signals different from a sinusoidal form. This contribution briefly reviews the basics of hybrid actuators and the oscillatory application in a linear motor. Then a hybrid relay is introduced as an example for quasi static operation. Based upon different drives enhanced strain-time characteristics of a hybrid stack actuator are theoretically and numerically predicted and verified by measurements. Finally a method of detecting the external mechanical load by measuring the resonant frequency will be explained. This could be applied to the linear motor, which can be enabled to identify its load without an additional sensor.

Key words: Piezoelectric actuator, magnetostrictive actuator, linear motor, injection valve, switching amplifier.

1. Introduction

Actuators with piezoelectric or magnetostrictive transducers reveal on the one hand the well-known advantages such as high forces and short response times and on the other hand the disadvantage of a high capacitive or inductive reactive power requirement. In order to attain the highest efficiency, it is indispensable to recover the

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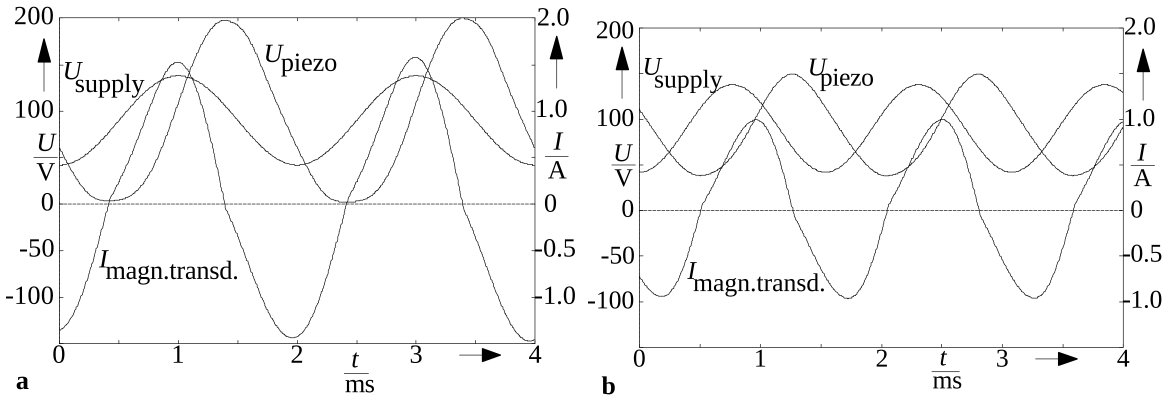
stored energy. To a certain extent, this can be achieved by employing switching amplifiers revealing the well-known disadvantages such as a rippled output-signal or problems with electromagnetic compatibility. A less complex circuit design is based upon an oscillating hybrid actuator. Here the reactive energy is exchanged between complementary transducer types, which have to be supplied externally just to compensate for the inner losses and the energy transferred into mechanical work. This minimisation of energy consumption is the main goal of our efforts, while researches in this field up to now mainly aimed at the improvement of mechanical aspects [1].

2. Basic principle of hybrid actuators

The simplest form of a hybrid actuator consists of a magnetostrictive and a piezoelectric transducer in mechanical series ("hybrid stack actuator") oscillating in their electrical resonance. To design the electrical drive we developed a simulation program taking into account

- the hysteresis of the voltage-strain characteristic of piezoelectric transducers
- the hysteresis of the current-strain characteristic of magnetostrictive transducers
- the capacity of piezoelectric transducers, which depends on voltage
- the current dependent permeability of magnetostrictive transducers
- the unsteady stiffness of transducers
- the effects of the external mechanical wiring (bias force, moving mass, damping).

Figure 1a shows the calculated progression of voltage and current when the hybrid actuator is driven at its natural frequency. A low-voltage stack transducer with a capacity of 4 µF is employed as piezoelectric actuator, the coil of the magnetostrictive transducer has an inductivity of 15 mH. Both transducers are mechanically prestressed with 200 N, the resultant electrical resonant frequency is 500 Hz.



The supply voltage must have an adjustable dc-offset to avoid a deleterious negative voltage at the piezoelectric transducer. However, it may be considerably smaller than the voltage required for the transducers. The supply only has to compensate for the energy transferred into mechanical work and the inner losses.

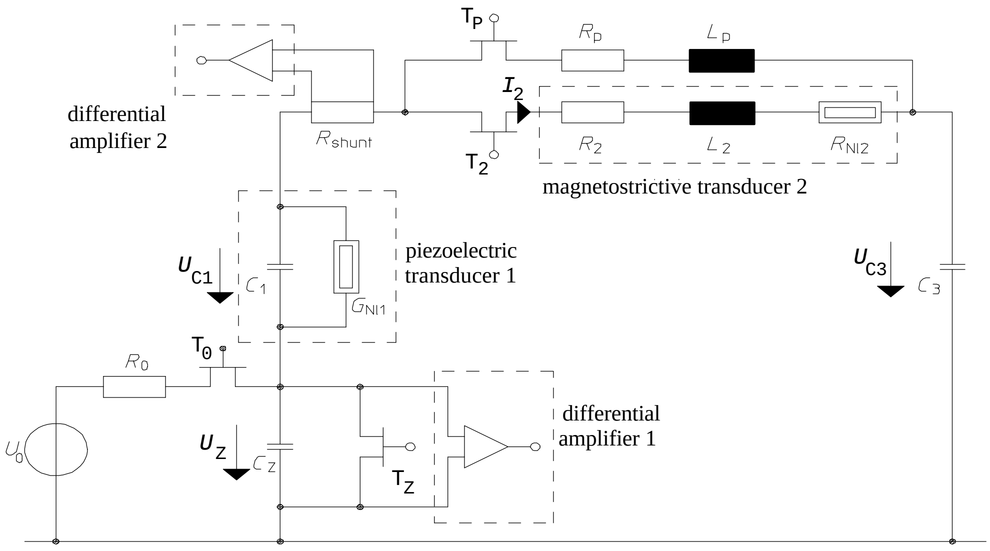
Driven at the resonant frequency, the voltage at the piezoelectric transducer and the current through the coil of the magnetostrictive transducer are shifted by a phase angle of approximately 90°. This resonant frequency, however, is strongly affected by the mechanical load. Figure 1b shows the progression of voltage and current when the hybrid actuator is driven with a frequency of 650 Hz - this corresponds to the electrical natural frequency if there is no mechanical load at all. The current and the voltage at the supply are no longer in phase and the efficiency is even lower as if the transducers would both be driven by a separate amplifier. To avoid this effect the circuit must be driven by a frequency-controlled oscillator. The output signal of the oscillator must be able to drive ohmic, capacitive as well as inductive loads. This is necessary because, due to the non-linearities, the impedance of the resonant circuit may be capacitive as well as inductive within one cycle, even if it operates at its resonant frequency.

Beside this effort for the driving amplifier another disadvantage of this fundamental idea is the non-variable operating frequency of the circuit. The coil is traversed by a bipolar current demanding a bias-magnetisation for the magnetostrictive transducer, which requires additional permanent magnets or electromagnets. Furthermore, an independent excursion amplitude is not possible since a variation of the displacement of the magnetostrictive rod could only be obtained by diminishing the current amplitude. This would also affect the voltage and thus also the strain of the piezo stack.

3. Linear motor with switching drive

To avoid the disadvantages mentioned above, the switching drive shown in Figure 2 has been developed [5].

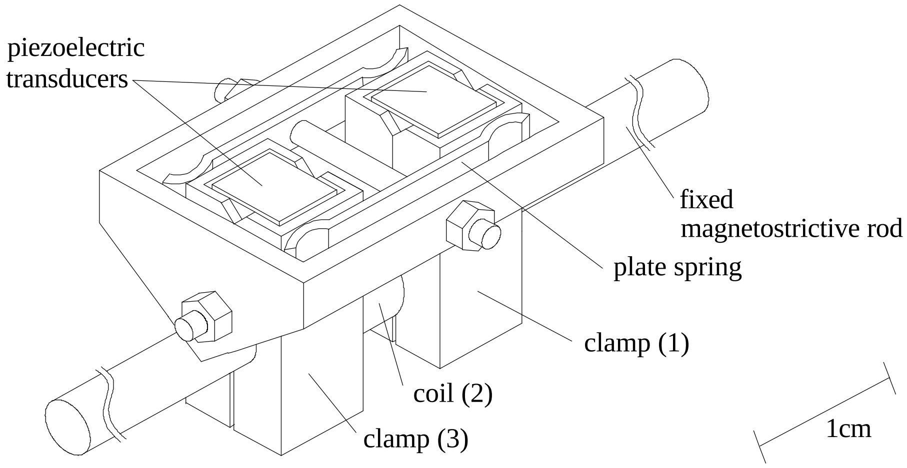
At the beginning of a cycle the voltage U_{C1} at the piezoelectric transducer 1 (C_1, G_{Nl1}) is the operational voltage U_0 and the additional capacity C_Z is charged to U_Z. By switching T_2, the current I_2 through the magnetostrictive transducer (L_2, R_2, R_{Nl2}) is released (phase 1 starts). T_Z bypasses C_Z, as soon as the differential amplifier 1 has detected voltage zero. The capacity C_3 is charged until the differential amplifier 2 recognises a current zero at the shunt. Then T_0 is blocked and T_P is opened (phase 2 starts) and the charge of C_3 is restored to C_1 by the auxiliary coil (L_P,R_P). When the differential amplifier 2 detects current zero again T_P opens and the cycle is complete. C_1 is again at the operational current U_0, T_Z is opened and C_Z may be charged for the next cycle with the help of T_0.



If the current ran through the non-premagnetised magnetostrictive transducer in phase 2, there would be a displacement in the same direction as in phase 1 cancelling the feed-forward altogether. To avoid a bias magnetisation, the current is directed through the auxiliary coil (R_p, L_p) in phase 2.

Regarding the displacement during a whole cycle, no strain is lost if the magnetostrictive transducer is designed in a way that it achieves its full stroke already in phase 1. The auxiliary coil may be designed with a small inductance and consequently with small resistance and small losses. Moreover, the displacement may be controlled by connecting the auxiliary coil already in phase 2, hence allowing a diminished displacement of the magnetostrictive rod. The maximum operating frequency is determined by the electrical components, any lower frequency may be attained by a space time interval just before beginning a new cycle.

As an application for a hybrid actuator with the switching drive a linear motor according to the inch-worm principle was developed [2] which is shown in Figure 3. Unlike linear motors already implemented [7] this construction consists of a fixed magnetostrictive rod and a movable coil which, together with the two clamps, forms the 'rotor'.



Clamp (1) and (3) are driven by piezoelectric transducers and clutch a magnetostrictive rod. At the beginning of the cycle, clamp (1) is closed and clamp (3) is open. The coil of the magnetostrictive transducer is traversed by a current and the magnetostrictive rod expands. The clamping changes from (1) to (3) and the coil is turned off. The magnetostrictive rod contracts to its original length. The clamping changes again from (3) to (1) - the 'rotor' has moved according to the displacement of the magnetostrictive transducer and one cycle is finished.

The displacements of the piezoelectric and magnetostrictive transducer must be shifted by a phase angle of 90°. So the hybrid actuator with the switching drive can be used in this motor just by replacing the capacitor C_3 (compare Figure 2) by a piezoelectric transducer for the second clamping. The clamping force is generated by the friction between clamp and the magnetostrictive rod and is thus proportional to the displacement of the piezoelectric transducers.

The simulation program was extended for the purpose of dimensioning this motor. For the clamps, stack transducers of a length of 10 mm and a capacity of 4 μF have been chosen, the inductance of the coil of the magnetostrictive rod resulted in 15 mH. The operational frequency is 650 Hz, i.e. at the calculated feed of 12 µm the motor develops a speed of 7.8 mm/s at a mechanical output power of 1 Watt and a maximum possible force of 130 N.

Although this arrangement does not use the active magnetostrictive material completely, it ensures the homogenous magnetic field configuration within the coil, it can do without further flux material and it thus contributes to a compact construction and miniaturisation of the entire system. Linear motors on the inch-worm principle have already been implemented in several ways, but in contrast to the well-known versions, the use of this hybrid actuator leads to innovations and has, due to the switching drive, many advantages:

- The operation is independent of the value of the external mechanical load

As shown in the previous analyses, the actuator is capable of adapting automatically to a change of resonant frequency due to different loads. The motor is then working at the highest degree of efficiency and the two piezoelectric transducers always operate at their operational voltage, which ensures a reliable clamping.

- Adjustable speed

  The start pulse for the movement of the motor can be controlled externally, e.g. by the microcontroller: So the speed is determined by clock pulse frequency, and is thus independent of load and can be adjusted between zero and the resonant frequency of the oscillation circuit formed by the transducers.

- Possibility of precision positioning

  A time-delayed connection of the auxiliary coil L_2/R_2 already in phase 1 of the motor movement (in which the magnetostrictive transducer is active) causes the displacement and consequently the feed-forward of the motor to reduce down to zero; this allows a precision positioning below the step-width of the motor.

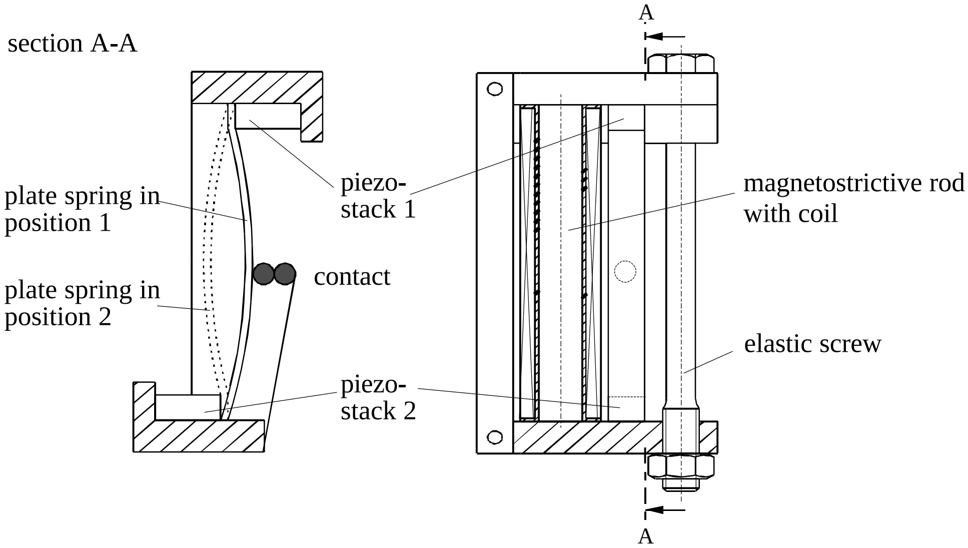
- High degree of efficiency

  When using hybrid actuators, the degree of efficiency is nine times higher than if the reactive power was not restored.

4. Hybrid relay

Although the linear-motor introduced above or a micro-pump with active valves are impressive examples for hybrid actuators in their resonant operation mode, further application fields are rare for two reasons: Neglecting the deformations from non-linearities the strain-time characteristic is always nearly sinusoidal. Moreover, the operating frequency is fixed to a single value. This restricts possible applications and so an extended performance of hybrid actuators was investigated.

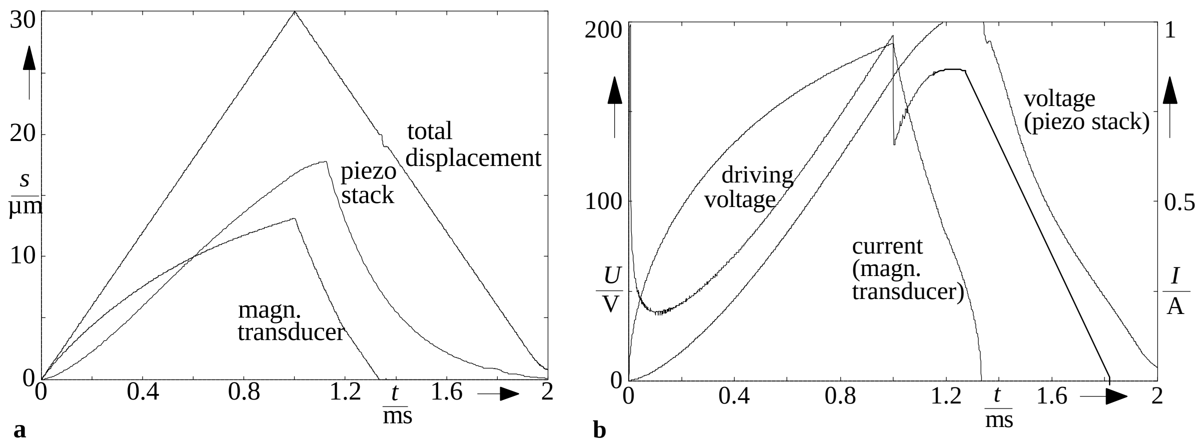
Piezoelectric transducers have the ability to retain their static deformation without energy consumption and so they are well-suited for low frequency operation. Based on this feature a hybrid relay was constructed driven by two piezoelectric stack transducers (Figure 4).



When the spring is located in position 1 piezo-stack 1 is charged until it finally produces a force large enough to move the spring into position 2 opening the contact. Piezo stack 1 can be discharged and the spring remains in position 2 until piezo-stack 2 is charged. Therefore only one of the two stacks is charged at the same time and a minimisation of the switching energy can be achieved by exchanging the charge between the transducers. For this purpose an inductor is needed which can be extended to a magnetostrictive transducer able to expand the mount of the spring leading to a larger bend in the end positions. In that way the contact force in closed state becomes larger and the distance in open state wider, which allows higher currents and voltages to be switched. The magnetostrictive transducer forms a hybrid actuator in combination with the two piezo stacks. It can be driven by the switching drive (compare Figure 2) and performs all the advantages of hybrid actuators pointed out in the previous chapters. The dimensions of the magnetostrictive and piezoelectric transducers are similar to those used in the linear motor and an electrical switching time of 2 ms can be achieved; this is much faster compared to a relay with an electromagnetic actuator.

5. Non-sinusoidal performance of a hybrid stack actuator

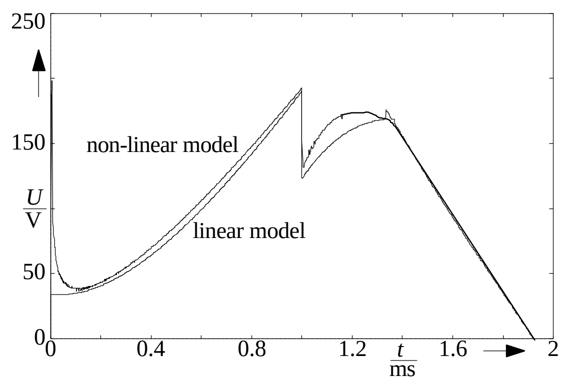
The relay introduced in chapter 4 shows that there are further possibilities to employ hybrid actuators if they are driven with frequencies that differ from resonance. Large application fields can be exploited if the strain-time characteristic of the hybrid actuator can be varied from a sinusoidal form. To achieve a desired non-sinusoidal strain-time characteristic the hybrid stack actuator has to be driven with an adapted voltage different from being sinusoidal. Figure 5 shows the calculated and measured linear strain-time characteristic of a hybrid stack actuator (low-voltage piezo stack transducer of 20 mm length with a capacity of 4 µF, magnetostrictive transducer of 15 mm length with an inductance of 15 mH, both mechanically prestressed with 200 N).

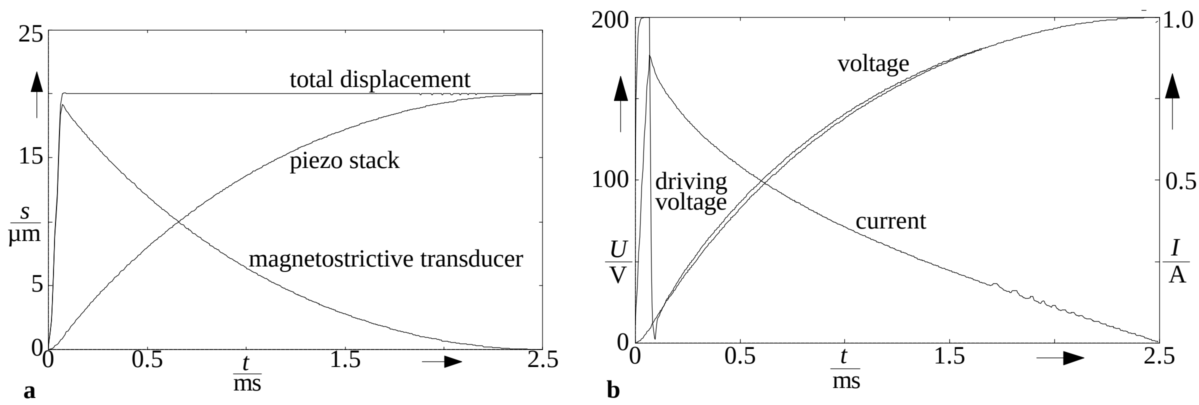


The addition of the strain of the single transducers results in the linear strain-time characteristic in Figure 5a. Figure 5b shows the voltage and the current of the transducers and the necessary driving voltage. This driving voltage was calculated iteratively with the help of a computer program considering the non-linearities and the hysteresis of the transducers.

Figure 6 represents a comparison of the driving voltage calculated with the non-linear transducer model and a driving voltage determined with a linear model. Although the progression is quite similar these two voltages differ obviously in some areas. Measurements have proved that the strain-time characteristic of the hybrid stack actuator driven with the voltage calculated with the linear model is far from being linear. This was to be expected because of the various non-linearities of the transducers and it confirms that the higher effort employing the non-linear model is unavoidable for an acceptable performance of the actuator.

Beside this continuous driving voltage a switching power supply can be applied just by providing the resonant circuit of the transducers with voltage zero or maximum. Because of the inductivity of the magnetostrictive transducer and the capacity of the piezoelectric transducer the voltage and the current within the hybrid actuator are always continuous and so the same voltage-current-time characteristic as shown in Figure 6 can be achieved with a switching power supply. So a switching power transistor can be employed as a supply simplifying not only the circuit design but also reducing the inner losses.



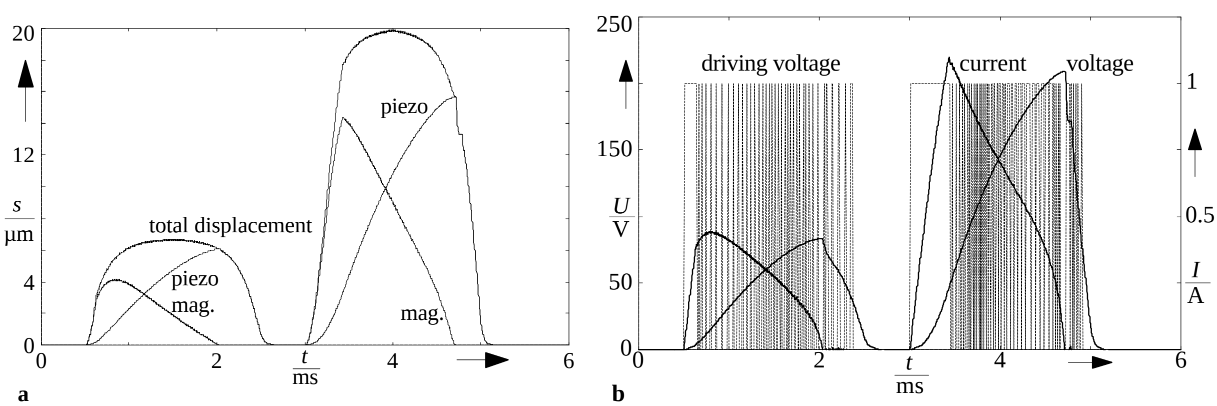


Solid state transducers are implemented when a high operating frequency or a fast switching function is needed. Such a nearly rectangular strain-time characteristic can be performed by a single piezo transducer requiring, however, a very high current peak that must be provided by the supply. A solution with a hybrid actuator also allows a very fast response time (Figure 7a), the current is comparatively low (Figure 7b) which allows a supply with a much smaller power output.

6. Injection valve

Injection valves for combustion engines are a most interesting application field for solid state actuators [4]. In contrast to valves with conventional actuators the high operating frequency of solid state actuators allows the forming of the injection progression. An injection progression as shown in Figure 8a optimises the combustion and reduces the noise and petrol consumption [3].

Such an injection valve can be implemented with a hybrid actuator Figure 8a shows the displacement of the magnetostrictive and the piezoelectric transducer needed to receive the desired injection progression. The voltage and current required for this progression are illustrated in Figure 8b. As input voltage a switching function can be used leading to the described simplification of the amplifier and to a reduction of the inner losses which is an important aspect for the employment in cars.



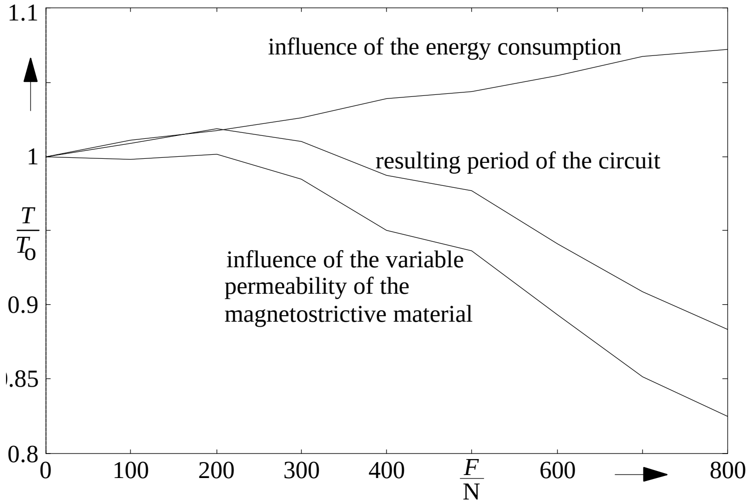
7. Utilisation of the inherent sensor effect

As stated out in the previous chapters the external mechanical load has a significant influence on the resonant frequency of the hybrid actuator. For this reason the switching drive was developed which allows the resonant circuit formed by the transducers to oscillate in its natural frequency making it independent of the load.

Investigations of the linear motor showed that there are two main factors which influence the period T of the resonant circuit: energy consumption because of mechanical work or inner losses and a change in the permeability of the magnetostrictive material because of different mechanical prestresses. These influences are illustrated in Figure 9.

The energy consumption leads to a nearly linear increase of the period T up to higher forces, the change in the permeability of the magnetostrictive material causes the inductivity of the exciting coil to decrease with higher forces shortening the period. Regarding the total period of the circuit there are three operating ranges worth to be studied in detail.

Driven in the range between 0 N and 200 N there is a slight increase of T mainly caused by the energy consumption. So an evaluation of the frequency allows an estimation of the mechanical load without an additional sensor. A difficulty in this operation range is that the magnetostrictive rod is hardly prestressed. This not only causes mechanical problems but also leads to an displacement of the transducer which is far from its optimum. An attempt to regard the period T as constant in the range between 100 N and 300 N with the aim to simplify the drive yielded poor results. In the range beyond 300 N (which represents a very suitable mechanical prestress) the period is approximately linear depending on the mechanical force. So the resonant frequency can be measured and the mechanical load easily be identified without an additional sensor extending the linear motor to a so called smart actuator. Furthermore this information can be used to detect overloads or changes in the material indicating a future failure.



8. Conclusion and outlook

Hybrid actuators with piezoelectric and magnetostrictive material reduce the energy consumption as well as simplify and consequently miniaturise the whole system. A linear motor according to the inch-worm principle can be constructed with a hybrid actuator allowing to detected failures or determine the external load without an additional sensor. Beside this sinusoidal working mode other strain-time characteristics can be achieved by a sophisticated drive opening a wide application field for hybrid actuators such as relays or injection valves.

Future work will examine the possibilities of improving the performance and efficiency of hybrid actuators in different applications as well as investigating other methods of utilising the inherent sensor effect of the employed materials (smart actuators [6]).

Acknowledgement

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References

[1] Butler, J.L., Butler S.C., Clark, A.E.: *Hybrid Magnetostrictive/Piezoelectric Tonpilz Transducer*. Journal Acoustic Society of America (1993), pp.636-641

[2] Clephas, B., Janocha, H.: *New linear motor with hybrid actuator.* Proceedings SPIE 3041 (1997), pp.316-325

[3] Dyberg, J.: *Magnetostrictive Rods in Mechanical Applications.* Proceedings First International Conference on Giant Magnetostrictive Alloys (1986)

[4] Janocha, H. (Ed.): *Adaptronics and Smart Structures.* Springer (1999)

[5] Janocha, H., Clephas, B.: *High Efficiency Linear Motor Utilizing Hybrid Actuators*, Proceedings Mechatronics (1996), pp.2.249-254

[6] Jones L.D., Garcia E.: *Novel approach to Self-Sensing Actuation.* Proceedings Spie 3041 (1997), pp.305-314

[7] Miesner, J., Teter, J.: *Piezoelectric/Magnetostrictive Resonant Inchworm Motor*, Proceedings. SPIE 2190 (1994), pp.520-527

Figure 1. Progression of voltage and current at a hybrid actuator driven **a.** in resonance **b**.out of resonance

Figure 2. Switching drive for a hybrid actuator

Figure 3. Linear motor on the inch-worm principle

Figure 4. Relay with hybrid actuator (front and side view)

Figure 5. Linear strain-time characteristic of a hybrid actuator **a**.strain of the transducer **b**.progression of voltage and current

Figure 6. Driving voltage calculated with a linear and non-linear model

Figure 7. Strain-time characteristic of a hybrid actuator for a rectangular function **a**.strain of the transducers **b**.progression of voltage and current

Figure 8. Strain-time characteristic of a hybrid actuator driving an injection valve **a**.strain of the transducers **b**.progression of voltage

Figure 9. Period of the linear motor depending on the force