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EXPERIMENTAL INVESTIGATIONS ON IMPACT TRANSMISSION THROUGH A PLATE

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Summary. *The concept of an impact actuated shift valve is presented. This valve concept can be actuated by different kinds of actuators, such as piezo stack actuators. A simplified model for the investigation of the impact process is created. The model consists of a plate, two spheres and a fluid-filled tank. Experiments are presented with and without fluids and different plates. The results are compared to simulations.*

1. INTRODUCTION

The typical function of a shift valve is to control fluid flow. One important aspect for some areas of the shift valves usage is media separation, meaning that there is no contact between the environment and the fluid within the valve. This is important, e.g. in cases where the purity demands for the media are extreme or the fluid is harmful. A new concept is based on impulse actuation, where the impulse needed to shift is transmitted through the casing. This concept is investigated in [1], where different prototypes are presented, using experiments, simulations and different tests. The tests include a vibration test, and a test for the number of shift cycles. Two of the prototypes are based on impact actuation using piezo actuators. There are two ways to use piezo actuators; one is to use a stack actuator directly by applying a high voltage to the piezo. Another possibility is to use a piezo bending actuator, which deflects a beam with an attached point mass which is discharged quickly, enabling the beam to swing back, initiating the impact. However, the problem with these prototypes is that they require a strong impact impulse in order to operate reliably. This is due to a low efficiency in the impact transmission.

In order to understand the physics influencing the efficiency of this transmission of impulse originating from an impact, a simplified experimental set-up is used to remove as many unknowns as possible. Therefore, a scaled-up model is created for more accurate measurements and a metal sphere is used for actuation. This allows to focus on the impact and its efficiency. The insight gained from these experiments is used to increase the efficiency of the impact process and to improve and verify the simulation models. The experiments are performed using two Laser-Doppler-Vibrometers to measure the displacement and velocity of the spheres. Several different materials and geometries for the plate are tested, especially with the influence of successive plastic deformations in mind.

2. CONCEPT OF AN IMPACT ACTUATED SHIFT VALVE

The proposed concept of a shift valve with separated media is based on a body inside the valve, which can be in two distinct positions. One position is allowing fluid flow and one is blocking the fluid flow as depicted in Fig. 1. It is the basic idea to transmit energy by an impulse wave or deformation from actuators ('open' and 'close') into the valve chamber to the sphere which will switch its position. A spring in the valve chamber prevents the sphere from an unintended shifting. On the other hand, the spring must not be too stiff, so that shifting is not impaired. The other two pictures in Fig. 1 show the design of one version and the prototype with two piezo stack actuators, which can be replaced by two piezo bending transducers.

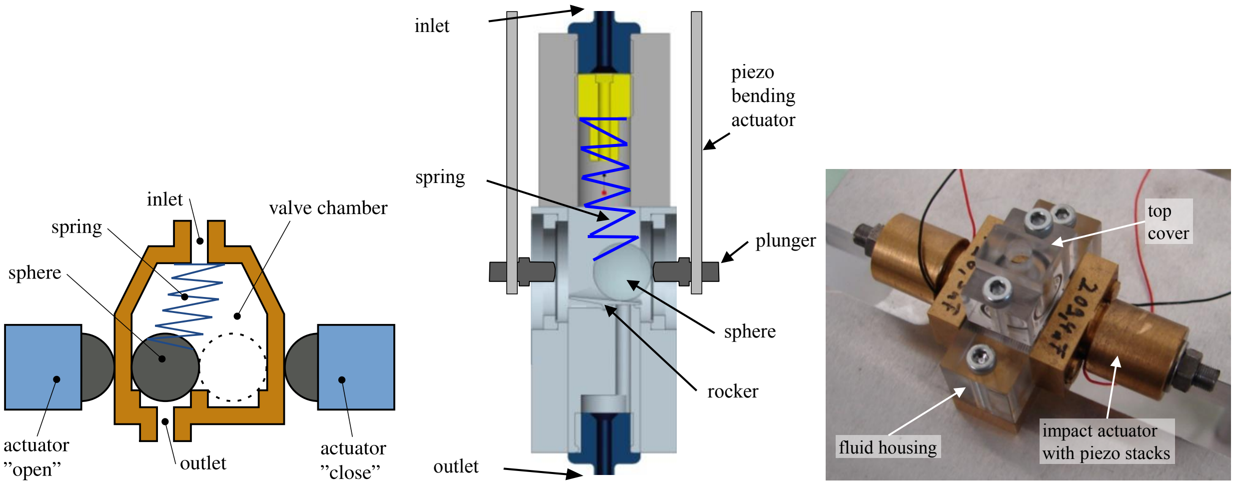

Figure 1. (Left) concept of the impact actuated shift valve, (centre) design with piezo bending transducers, (right) prototype with piezo stack actuators

This concept is promising for applications where media separation is relevant and the periods in the same state are relatively long. Other advantages are the possibility to use only inert materials allowing MRT safety, the bistability allows low energy consumption, in case that the valve keeps one of both states for longer times. Also, many different actuators can be used, e.g. piezo actuators, hydraulic actuators, electromagnetic, pneumatic or even manually powered. More details about different designs, their performance, design criteria and tests are available in [1] and [2].

With respect to the requirement of MRT safety for an implantable device, two different piezoelectric actuators were investigated as they contain no ferromagnetic materials. Besides this, an electromagnetic impact actuator with a lift magnet was investigated as a possible actuator for many other applications. This type of actuator is suitable for most industrial applications, as it is available at relatively low cost and also has no special requirements concerning the electronics.

The piezo stack actuator applies abruptly a high voltage to the piezo ceramics that leads to a fast elongation of the piezo stack which causes the impact. For the generation of the high voltage a step-up converter is used, which requires a well-dimensioned buffer capacitor.

The piezo bending actuator is used directly as a high voltage capacitor in the step-up circuit, that transforms the supply voltage of the battery. First, the bending transducer is loaded to full capacity, which means that it has stored a large amount of strain energy. The actuator is then short-circuited using a resistor, which allows that the actuator is discharged faster than the time it needs to reach its straight position with maximum kinetic energy.

3. EXPERIMENTAL INVESTIGATIONS

In order to understand the physics influencing the efficiency of this transmission of impulse originating from an impact, a simplified experimental set-up is used to remove as many unknowns as possible. This simplified model is scaled-up, as this makes it easier to handle and gives more accurate results. A metal sphere is used for actuation. The simplified model is sketched in Fig. 2. This allows to focus only on the impact and its efficiency. The insight gained by these experiments is used to increase the efficiency of the impact process and to improve and verify the simulation models.

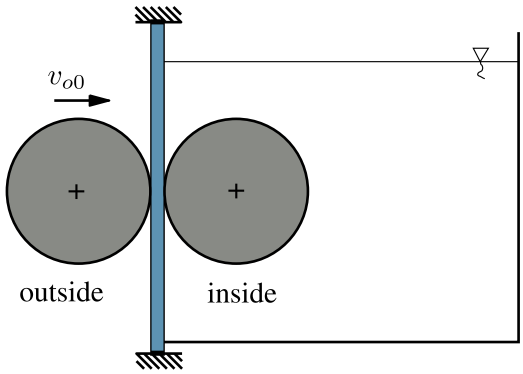

Figure 2. Simplified model for the impulse transmission in an impulse actuated shift valve

To get a scaled-up model, the plate is scaled such that it has the same radius to thickness R/t ratio as in the real valve. The spheres are scaled, such that the resulting contact time has the same ratio to the period of the first eigenfrequency. The geometrical data of the chosen model is summarised in Table 1, including the initial velocity.

Experiments were performed to investigate the influence of different fluids and the influence of different plates which represent the casing of the shift valve where the impulse will be transmitted. The experiments are also important to validate the simulation models, which are

Table 1. Geometrical data and initial condition of the scaled model

	outer sphere	plate	inner sphere
r (mm)	10	33	10
t (mm)	-	2	-
v_0 (mm/s)	-610	0	0

used to create design guidelines for the design of prototypes. The most important result of both experiments and simulations is the efficiency

$$\eta = \frac{T_{\mathrm{i}1}}{T_{\mathrm{o}0}} , \tag{1}$$

which relates the kinetic energy of the inner sphere after impact with the kinetic energy of the outer sphere before impact. It is also possible to alternatively consider the strain energy of a bending transducer or a stored electric energy here.

3.1 Experimental set-up

An experimental set-up similar to the set-up in [3] is used, which is based on laser Doppler vibrometers (LDVs) to measure displacements and velocities with high frequencies ($f < 100\,\mathrm{kHz}$). The set-up is shown in Fig. 3 with the plate and the release mechanism. The two LDVs are mounted to the left and right, aiming at the spheres. The plate, which is ideally clamped in the simulation, is mounted on an aluminium frame in the centre. The two spheres are suspended by thin high-modulus polyethylene wires which are connected to the spheres by small copper plates, glued on them. The sphere which represents the actuation of the valve is released by a flap, which is released by an electromagnet.

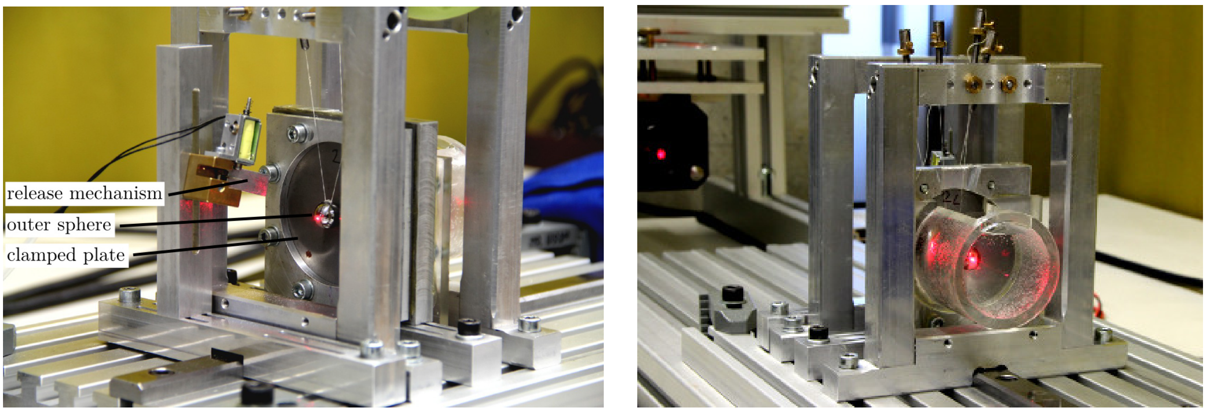

Figure 3. Test-bed for experimental verification with removable tank for experiments with different fluids

The LDVs measuring the displacements and velocities are made by Polytec GmbH. One LDV is placed on the outside, measuring the sphere at the impact. This means that this sphere moves into the laser beam just before impact. The second LDV is placed on the opposite side which represents the interior of the valve, also measuring the centre of the sphere. Using both LDVs gives a displacement signal and a velocity signal for each sphere.

3.2 Evaluation of the measurements

A typical velocity signal, created by the two laser Doppler vibrometers is plotted in Fig. 4. The signal of the outer sphere can be used almost directly. There are no influences caused by a liquid. Therefore, the velocity of the outer sphere can be used directly after subtracting the velocity offset, which can be determined with the displacement signal.

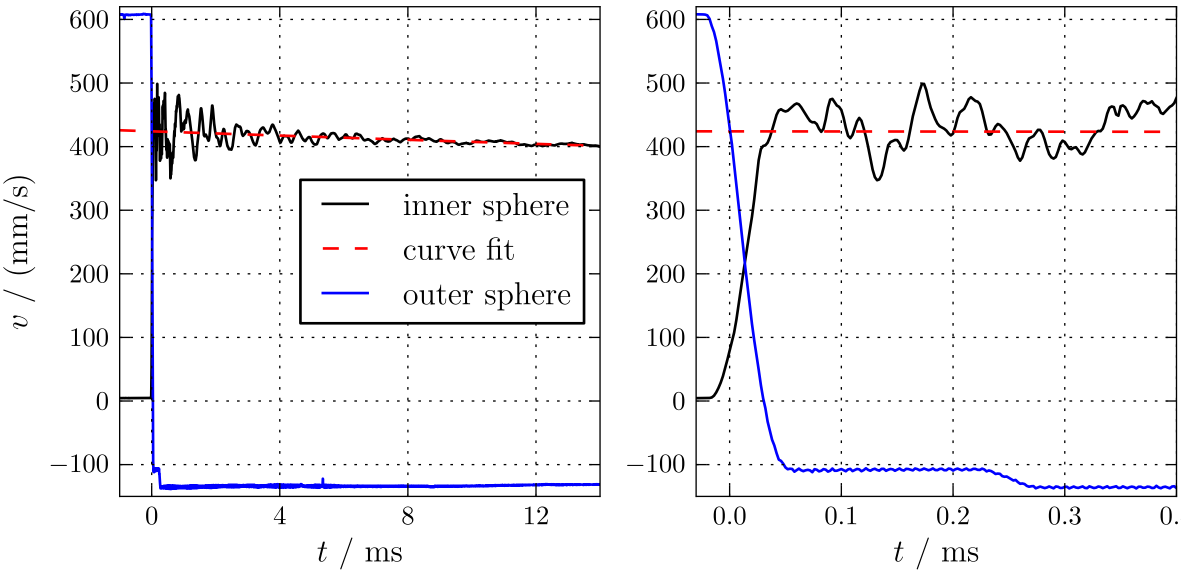

Figure 4. Measured velocity signals of the inner and outer sphere, and the recovered sphere velocity. Left: large time scale; Right: detail of the impact

The velocity signal of the inner sphere is not the actual velocity of the sphere. This will be discussed in the following sections.

3.2.1 Influence of the refractive index on the frequency shift

The measured velocity signal must be corrected by the relation between frequency shift and the relative velocity. According to [4], velocity measurement with the Doppler effect creates twice the Doppler frequency shift, because the measurement device is both, sender and receiver. Thus, the frequency shift is

$$\Delta f = 2 \frac{v}{c_{\text{fl}}} f_0 \tag{2}$$

and depends on the velocity of the sphere v, the phase velocity of light in the medium (fluid) c_{fl} and the frequency of the laser f_0. The refractive index is defined as

$$n = \frac{c_{\text{fl}}}{c_{\text{vac}}} \ . \tag{3}$$

The controller of the LDV uses Eq. (2) to determine the velocity and assumes that the medium is vacuum or air. Therefore we can calculate the true velocity in the fluid using the refractive index from Eq. (3)

$$v = \frac{v_{\text{controller}}}{n} \ . \tag{4}$$

For the different fluids used in this work, the refractive indices are listed in Table 2. The refractive index for air is approximately one, which means that there is no compensation required for measurements in air.

Table 2. Refractive index n, density ρ and dynamic viscosity μ for the used fluids

	n	$\rho\,(\text{kg/m}^3)$	$\mu\,(\text{mPas})$
water	1.33	1000	1
vegetable oil	1.46	930	64
hydraulic oil	1.46	890	50
air	1.0003	-	-

After having corrected the velocity signal from the LDV, there is a slight offset that must be subtracted. That is possible because the drift, which is responsible for the offset, is slow. For the sphere in the valve, this offset is simple to determine, because the velocity at the beginning is known to be zero.

3.2.2 Influence of the drag force

The velocity of the sphere in the valve is decreased considerably after the impact compared to the impact without liquids. The required velocity for the efficiency calculations is just after the impact; however, the velocity signal of the sphere is superimposed by high frequency oscillations, whose origin will be discussed later. Therefore, it is necessary to use a longer interval, where the influence of these oscillations cancels out. Instead of using a mean value which is based on the assumption that the velocity of the sphere is constant, we derive a function which describes in general the velocity of a sphere slowed down by a liquid. This function is used in the post-processing of the experiments to make a curve fit and determine the velocity of the sphere just after impact. The equation of motion of a point mass, slowed down by a drag force, is

$$m\dot{v} = F_{\text{d}} \quad \text{with} \quad F_{\text{d}} = -av^2 \tag{5}$$

where F_d is the drag force which is proportional to the square of the velocity for sufficiently large Reynolds numbers ($Re > 1000$). This is a Bernoulli type differential equation, which can be solved by division with v^2 and using the substitution $u = z^{-1}$. This leads to the equation

$$\dot{u} = \frac{a}{m} \; . \tag{6}$$

Integrating over time and back-substitution results in

$$v = \frac{1}{\frac{a}{m}t + c} \tag{7}$$

with the integration constant c. This function depends on the two parameters a and c, which can be determined using a curve fit.

For lower Reynolds numbers, in the transition area between laminar and turbulent flow ($10 < Re < 1000$), the drag force can be described approximately by $F_\text{d} = -av^{3/2}$. The resulting differential equation is also of Bernoulli type and its solution is

$$v = \frac{1}{\left(\frac{a}{2m}t + c\right)^2} \; . \tag{8}$$

This method is used to create the red dashed curve fit in Fig. 4. The measurement in this figure is with hydraulic oil. Therefore, the fit is performed using Eq. (8) because the Reynolds number is less than 1000. The fit is performed for $t \in [0.2, 14]\text{ms}$ using a standard least squares algorithm. For a varying start of the time interval between 0.2 and 3 ms the resulting velocity is $425\,\text{mm/s} \pm 0.6\,\%$. This small variation shows that this method is robust enough for the evaluation of the measurements.

3.2.3 Vibrations superimposed on the sphere velocity

There are different possible reason for the superimposed vibrations on the measured velocity of the sphere in the fluid-filled tank. Firstly, if the sphere actually moves with the measured velocity, the large accelerations after the impact must be caused by large forces due to the relatively large mass. This is not likely, considering possible fluid forces acting on the sphere. Therefore, there must be other reasons related to the measurement method and the path that the light travels. The principle of the measurement of the LDV is basically a measurement of the derivative of the length of the optical path from the laser to the moving object and back, compared to a reference length. This is known as the principle of the Michelson interferometer [4]. The measured velocity is thus, formulated more general,

$$v_\text{measured} = \frac{\text{d}}{\text{d}t} \sum_i x_i n_i = \sum_i \left(\dot{x}_i n_i + x_i \dot{n}_i \right) \; , \tag{9}$$

where the optical path is separated into segments of different fluids x_i. According to this, a variation of the refractive index n along the optical path leads to a measured velocity. This can be caused by density fluctuations in the fluid due to compressive waves, which are caused by the impact. Density fluctuations in a fluid change the refractive index locally varying with time and position. However, according to [5], the refractive index of water varies for pressures between 1 and 100 bar between 1.330 and 1.335. This influence is very small and can not explain the vibrations in the velocity signal.

The only remaining explanation is, that the tank, where the laser passes, moves and causes the vibrations. Due to the movement of the whole tank, the lengths x_{air} and x_{fluid} change, which causes the measured velocity. This vibration is also observed when the velocity of the surface of the tank is measured, which further supports the presented explanation.

3.3 Experiments with different plates

Measurements without the added complexity of a fluid are easier. Also simulation models without fluid are much simpler, and can be validated much easier. Many effects that occur, are also present in the case without fluid, which means that we can try to gain insight from the investigation of the impact without a fluid. The experiments are performed with different plates, whose material data are listed in Table 3. The steel and the aluminium plates have a thickness of 2 mm and the stainless steel plate of 1.5 mm.

Table 3. Material data: Young's modulus E, density ρ, and Poisson ratio ν

	E (MPa)	ρ (kg/m^3)	ν (−)
steel plate	210000	7780	0.3
stainless steel plate	200000	8000	0.3
aluminium alloy plate	73000	2790	0.33

The three plates were tested in an unused state, however only for the steel plate the first impacts were captured properly, as can be seen in Fig. 5. Variations due to the evaluation of the measurements are shown as error-bars. The marker is positioned at the median. The uncertainty in the evaluation is caused by a drift in the velocity signal. This drift is caused by a filter in the LDV's controller which cannot be disabled. The efficiency, as defined in Eq. (1), increases for all three plates due to plastic deformations that occur at the beginning and reach a steady state after several impacts. Detailed investigations on plastic and visco-plastic material in simulations and experiments of spheres on bars are described in [6]. However, in a shift valve the first impact plays only a minor role, because the shift valve is used more than just once and the first few impact can be made already during production.

The steel plate reaches a steady state efficiency of 67 %, the stainless steel plate 69 % and the aluminium plate 78 %. This agrees with the findings of the simulation models, where a low Young's modulus for the plate is beneficial for the energy transmission. Further comparisons to the simulation results follow in the next chapter.

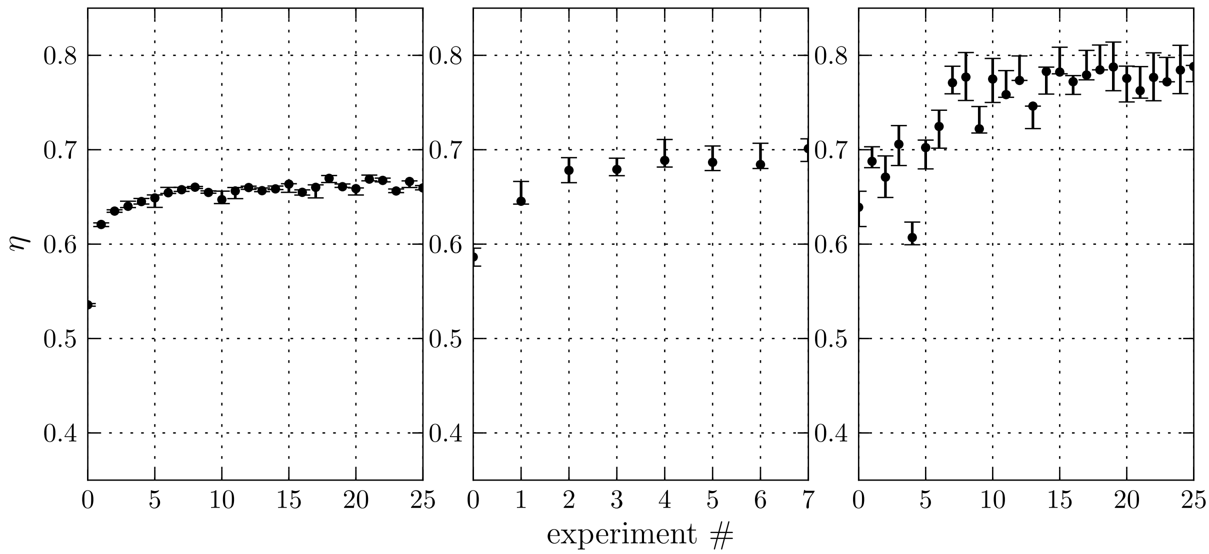

Figure 5. Efficiency for different plates: (left) 2 mm steel plate, (middle) 1.5 mm stainless steel plate, (right) 2 mm aluminium plate

3.4 Experiments with different liquids

Experiments with water, vegetable oil and hydraulic oil were performed using a steel and an aluminium plate with 2 mm thickness according to the model data listed in Table 1. Adding an acrylic tank adds a few complications for the measurements including a more difficult alignment of the set-up, the previously discussed problems with the influence of the refractive index, superimposed vibrations, and reflections from surfaces other than the sphere in the tank. Light, that is reflected from surfaces other than the sphere, is mixed in the LDV's head and leads to jumps between different velocities; mostly the sphere velocity and velocities around zero coming from different points on the tank.

The efficiencies are calculated from the velocities, which in turn are determined by applying the correction for the refractive index from Eq. 4 and the method to determine the velocity after impact by using a curve fit of Eq. 7 for water and Eq. 8 for oils. The error-bars show the variation from several experiments, including the variation from the evaluation. The variation in the efficiencies is relatively small. However, there are also other sources for errors in the set-up and execution of the experiments which are not included in the error-bars.

The major influence on the efficiency is the plate material and its geometry. The used liquids have a similar influence on the efficiency despite their different viscosity. This is a very interesting outcome and shows that fluid effects, where the viscosity has the primary influence, can not be overly relevant. The overall efficiency drop compared to the dry impacts, is 18-24 % for steel and 20 % for aluminium. Compared to the total efficiency drop, the influence of the type of fluid is small.

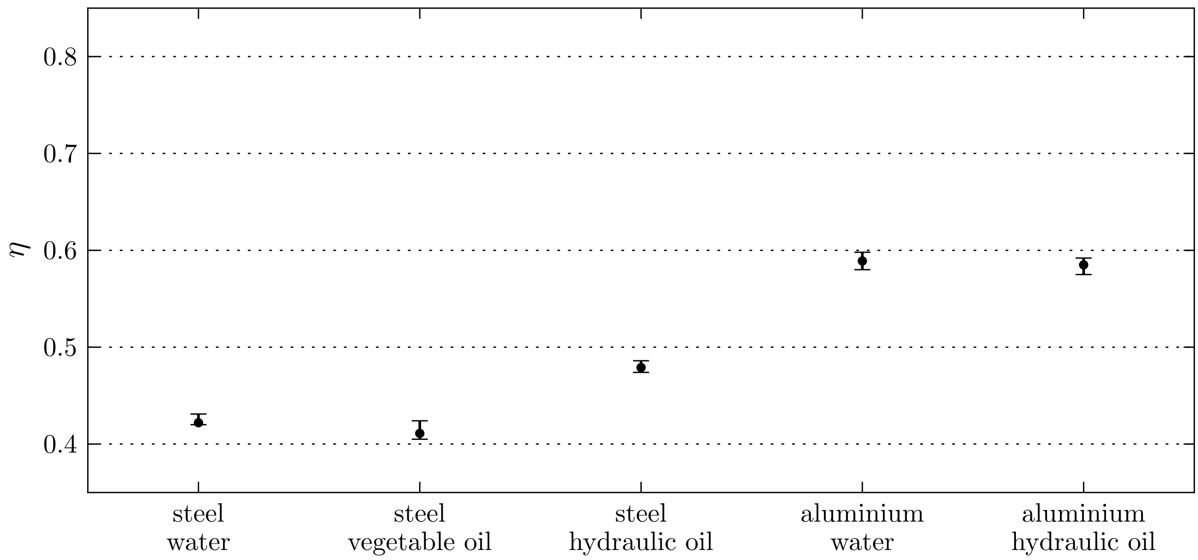

Figure 6. Efficiency for a 2 mm steel plate and a 2 mm aluminium plate with different fluids

4. SIMULATION MODEL AND RESULTS

To achieve an understanding of the impact behaviour and the parameters influencing it, a very flexible and fast model, which also allows optimisations and parameter studies, was created. Usually detailed analyses of impact are done with finite element simulations but here an elastic multibody system is used in order to reduce the model complexity and simulation time. A finite element simulation is only used to validate the simulations without fluids, for all other simulations an elastic multibody model is used. The model consists of three bodies, as shown in Fig. 2. Two rigid bodies for the inner and outer spheres, and an elastic plate. Two impacts occur at the same time, one between the outer body and the plate and the second between the plate and the inner body. Both are modelled with the Hertzian contact law.

Fluids are included only by an approximate model for the fluid-added-mass effect. Experiments with a vibrating steel plate in the tank show a decrease of the first eigenfrequency to one third, other eigenfrequencies are influenced differently. Also by adding a sphere close to the plate, the influence of the fluid changes. However, such a decrease in frequency can be reached by adding homogeneously additional mass on the plate of about 9 times the plate mass. This is surely an upper limit, only occurring for the first eigenfrequency and without inner body. The used models are described and evaluated in [1]. In [3], a similar model is proposed and used for impacts of spheres on bars.

The used elastic multibody model is created in a modular way, where all parameters can be changed quickly and the outer body can be replaced by a mechanical model of a piezo bending transducer. The simulation results using this model and linear material can not be exactly as measured due to not considered nonlinear material effects. However, the results are close and represent the influence of different material properties, such as Young's modulus and density.

The results of simulations are compared to experiments in Table 4. The results represent the general behaviour. For the dry impact, except for the thinner stainless steel plate, the results are in reasonable agreement.

Table 4. Efficiency comparison between experiments and simulation, with and without oil

	$\eta_{ex,dry}$	$\eta_{sim,dry}$	$\eta_{ex,oil}$	$\eta_{sim,oil}$
2 mm steel plate	0.66	0.69	0.43/0.48	0.43/0.48*
1.5 mm stainless steel plate	0.69	0.76	-	0.56/0.60*
2 mm aluminium plate	0.78	0.81	0.59	0.52/0.58*

The fluids are accounted for by adding mass homogeneuosly to the plate accordingly. The efficiencies marked with a (*) are generated with an assumed fluid added mass such that the efficiency for the steel plate is the same as in the experiment. This means that for 43 % efficiency, the fluid added mass must be 4 times the steel plate mass, and for the 48 % efficiency, the fluid added mass is only 2.5 times the steel plate mass. The simulation for the stainless steel plate and the aluminium plate were performed with the same fluid-added-mass. For the lower value of the added mass, the efficiency is predicted very well. This shows that it is possible to explain the efficiency drop with the fluid-added-mass effect. However, this effect must be modelled in a more detailed manner in the future, in order to predict its influence on the efficiency. Many detailed investigations about the influence of different parameters and the performance of a piezo bending transducer were performed in [1]. A next step will be to find an optimal force signal created by a piezo stack actuator to achieve a high efficiency and therefore good transmission of the created impulse.

5. CONCLUSIONS

In order to understand the physics of the impact in an impact actuated shift valve, a scaled experimental set-up is created which is used to validate simulation models and find relevant influences. In order to perform LDV measurements of a submerged body, several considerations and corrections were required in order to determine the actual velocity of the moving sphere in the tank. The results from experiments indicate that fluid effects, which depend on the viscosity play only a minor role. The results can be explained by the fluid-added-mass effect. It is important, that the added fluid does reduce the efficiency as one would expect, but does not render the concept impossible.

Acknowledgements

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