Influence of Operating Conditions on the Fluidic Ultrasonic Transducer Signal

Benjamin Bühling[1,*], Thorge Schweitzer[2], Stefan Maack[1], Christoph Strangfeld[1]
[1] *Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany*
[2] *FDX Fluid Dynamix GmbH, Rohrdamm 88, 13629 Berlin, Germany*
[*] *Corresponding author, Email: benjamin.buehling@bam.de*

Abstract

While contact and immersion ultrasonic testing are established methods in non-destructive testing (NDT), generating high power air-coupled ultrasound remains a challenging task. Solutions often involve setups that are restricted to lab environments. When field measurements are required, such as in NDT for civil engineering, a handy, robust and safe transducer is needed. For this purpose, an ultrasonic transducer based on a fluidic switch has been developed. A sonic air flow inside the device is switched rapidly so that an ultrasonic signal is generated. Both theory and previous flow simulations suggest that the control flow pressure ramp has only little influence on the switching time of the device. This publication gives an overview over the operating principle of the fluidic ultrasonic transducer and investigates the influence of control tube length and pulsing repetition rate on the ultrasonic pressure amplitude. High repetition rates are found to reduce the signal amplitude, whereas long tubing has only little negative influence on the amplitude while improving signal quality.

Introduction

Ultrasonic (US) testing is a well-established method for characterization and damage detection in non-destructive testing [1]. To introduce the US pulse to a specimen, it needs to be coupled to the transducer. As applying a coupling liquid to the transducer-specimen interface is time consuming, immersing the entire specimen into such a liquid allows for faster testing [2]. The use of air-coupled ultrasound (ACU) is a viable alternative for specimens that are not movable to liquid tanks or are damaged by couplants [3]. As a concept to tackle the challenge of increased impedence losses [4] posed by ACU, the use of a fluidic transducer for US generation has been proposed by Bühling *et al.* [5], presenting an analysis of the switching process and the resulting US field.

The fluidic transducer is based on a fluidic switch (also called fluidic amplifier), which was initially developed for mechanical logic circuits [6]. A fluidic switch is supplied with a pressurized fluid, that is switched between two outlets by activating a control flow. This control flow redirects the main flow coming from the supply port, which remains stable in its direction even after the control flow is turned off. The respective activated outlets represent the two possible states of the switch, *on* and *off* and thus enables binary logic. The fluidic transducer utilizes the fast switching property of the device, as the induced rapid mass flow fluctuation at the activated outlet port generates US waves.

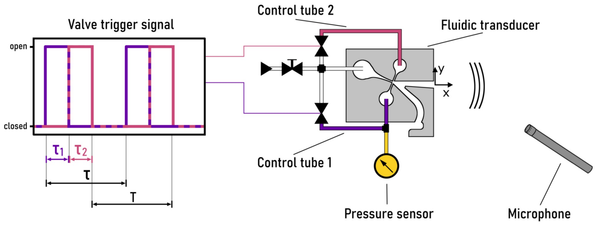

Figure 1: Experimental setup, where $\tau_1 = \tau_2 = 15$ ms are the opening intervals of the control valves. Both control tubes have length L.

Most of the literature on fluidic switch design parameters is concerned with the effects of the device's internal design parameters on the switching behavior [7–12]. As fluidic switches have mainly been used for control purposes, their optimization criteria were stability of the stable states, reliability of switching and overall switching time. Analytic descriptions were not intended to describe the high Re flow acoustics found in the fluidic transducer. The study of external component influence was mainly intended to prevent resonance circuits in fluidic component networks [6]. Schweitzer *et al.* [13] presented a numerical study on the influence of operation conditions on the flow switching behavior of a fluidic amplifier. Their findings show only little influence of the control pressure ramp on the switching action. However, downscaling of the geometry and increasing supply pressure were found to reduce switching time. However, the assessment concerned only the flow behavior, not the resulting acoustics.

While the air flow through the supply port of the fluidic transducer can be considered passive in the switching process, the influence of the active control flow operation parameters need to be investigated. While elasticity of the tubing may alter the slope of the control pressure ramp, added volume of tubing and switching repetition rate potentially influence the ramp's starting level. Thus, the study presented here evaluates experimentally the influence of the control tube length and the pulsing repetition rate on the US pulses generated by a fluidic transducer.

Setup and Methods

The fluidic transducer used in this study is the same as the one investigated in a previous publication [5]. It was designed by FDX Fluid Dynamix company (Germany) and was manufactured at the Federal Institute for Materials Research and Testing (BAM). Deviating from the previous mode of operation, the process of switching *off* was controlled actively using a second valve. Fast switching MHJ10 air valves (Festo Company, Germany) were used for control port activation and a calibrated MK301 measurement microphone (Microtech Gefell company, Germany) for acoustic pressure measurements. The microphone was placed in the $z = 0$ mm plane, at a distance of $x = 100$ mm and $y = 50$ mm from the transducer outlet, as shown in figure 1. Polyurethane tubes with an outer diameter of 6 mm and an inner diameter of 4 mm were used to connect the pressure supply, control valves and transducer. The static supply pressure was $p_0 = 2$ bar. The static pressure at control port 1 was measured using an amplified HDOB005 compensated pressure sensor (First Sensor, Germany) with a response time of 0.1 ms. The tube leading to the sensor had a length of 110 mm. The data was recorded at a sampling rate of 500 kS/s using a USB-6361 (National Instruments company, USA) DAQ device.

Both the repetition rate of the transducer and the length of the tubing between the control valves and control ports were varied, with values given in table 1. The for all parameters, $N = 400$ switching cycles were recorded. These switching cycles were acquired in sets of 20 and 40 pulses for the repetition rate and tube length variations, respectively. For comparison of the US pressure and to account for the microphone frequency response, the microphone data was band-pass filtered in the $20 - 100$ kHz range. To find the maximum amplitude of a pulse, a time frame Δt_p of 1500 samples was defined in which the pulse occurs in every switching cycle, similar to the previous publication [5]. A snippet of a time signal with highlighted events of the switching cycles is shown in figure 2. Unless stated otherwise, the maximum absolute microphone signals $a_{max}(\Delta t_p)$ of these were averaged over all $n = N$ cycles, so that

$$\bar{a} = \frac{1}{n}\sum_{k=0}^{n} a_{max}(\Delta t_p) \tag{1}$$

To relate $a_{max}(\Delta t_p)$ to the maximum noise amplitude created by the flow in the *on* state (Δt_{on}), a signal quality indicator SQI is introduced as

$$\mathrm{SQI} = \frac{a_{max}(\Delta t_p)}{a_{max}(\Delta t_{on})} \tag{2}$$

with $\overline{\mathrm{SQI}}$ being the average of this value over all switching cycles, similar to eq. 1.

Table 1: Parameters used in this study: tube length L, pulse separation τ and the corresponding repetition rate $1/\tau$. Bold values were held constant, as the other respective parameter was varied.

L [mm]	τ [ms]	$1/\tau$ [Hz]
50	60	6.7
100	80	12.5
150	100	10.0
200	120	8.3
250	**140**	**7.1**
300	160	6.25
350	180	5.6
	200	5.0
	220	4.5
	240	4.2

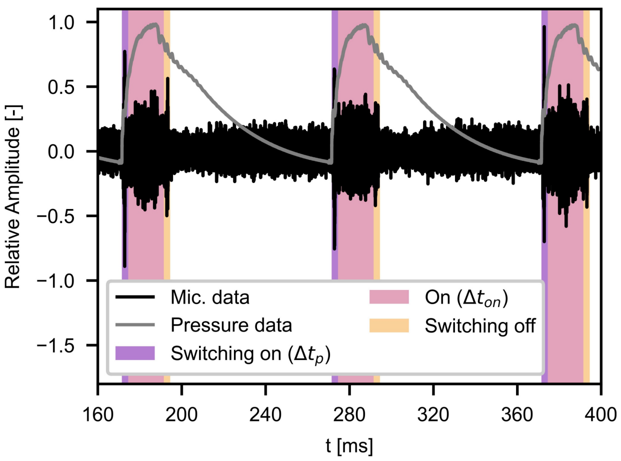

Figure 2: Microphone and pressure sensor time signals of the switching cycles with $L = 200$ mm and $\tau = 100$ ms. In the non-highlighted sections the transducer is in *off* state.

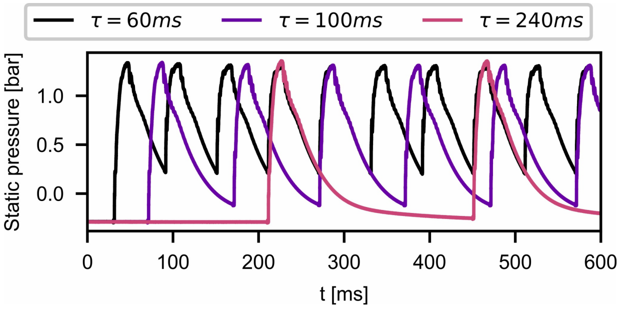

Figure 3: Pressure sensor signal for selected pulse separations τ.

The recorded pressure data captures the behavior of static pressure in control tube 1, analogous to the pressure ramp simulated by Schweitzer et al. [13]. This static pressure is varying much slower than the acoustics, so that the time response of the sensor suffices. The minimum and maximum static pressures ($\bar{p}_{min}$ and $\bar{p}_{max}$, respectivley) refer to the time span T of a whole switching cycle.

Results and Discussion

Using the setup described above, the fluidic transducer signal is examined. First, the pulse separation and secondly, the control tube lengths is varied according to table 1.

Pulse separation

The repetition rate influences the switching process as it limits the time in which the system can return to its initial *off* state after the switching cycle is completed. To investigate its influence on the US generation purpose, the microphone signal is compared to the pressure signal. Figure 2 shows both signals together with the time intervals of the switching cycles. When the fluidic

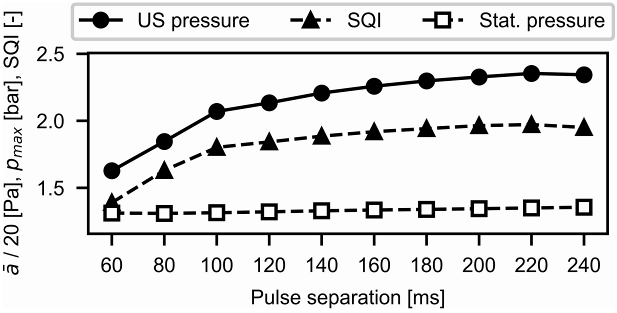

Figure 4: Mean microphone and pressure sensor amplitudes and signal quality index for varying pulse separations τ.

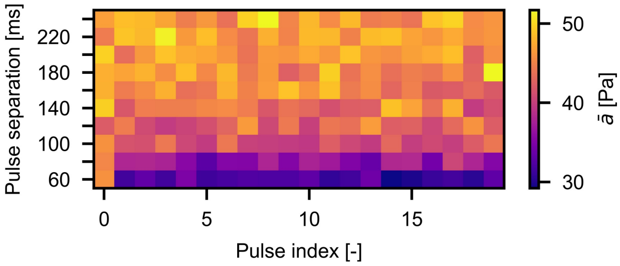

Figure 5: Mean microphone amplitude of the individual pulses in the pulse train for varying pulse separations τ.

is turned off, the pressure sensor records a negative pressure, which is caused by the high speed flow passing by the control port (Venturi effect). As the control valve is opened, the static pressure increases rapidly, causing the main flow to switch. The pressure falls as the control valve is closed again and the opposing control valve is opened. The comparably slow decline in static pressure is caused by the capacitance, induced to the system by the tube volume and the compliant tubing material. As shown in figure 3, for all repetition rates investigated, the initial pressure in the first control tube is not fully regenerated as the next switching cycle is initiated. Thus, the fluidic transducer would require more time to return to its initial state. However, US pulses are generated despite the pressure not fully returning to its initial values between the pulses.

Figure 4 shows the average peak pressure with varying pulse separation times τ, i.e. regeneration times. Higher pulse separation times result in a higher US amplitude, leveling off τ = 180 ms, while the maximum static pressure is almost constant. This behavior shows that $\bar{a}$ is not affected by the maximum pressure as the switching process takes place when a threshold pressure is exceeded, which is before the p_{max} is reached. $\overline{\mathrm{SQI}}$ shows the same behavior as the US amplitude.

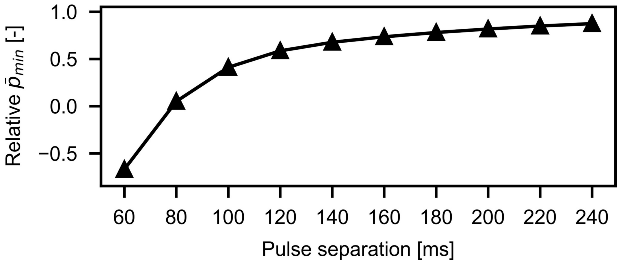

Figure 6: Mean relative minimum pressure of the follow-up pulses in the pulse trains for varying pulse separations τ.

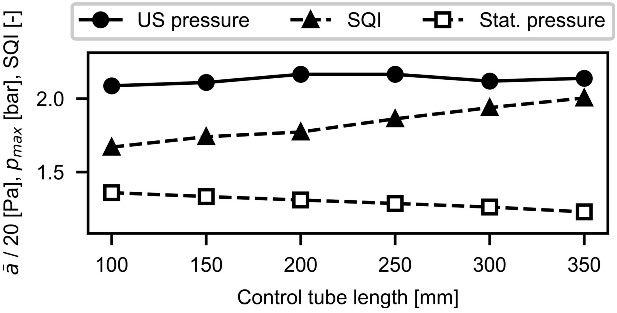

Figure 7: Mean microphone and pressure sensor amplitudes and signal quality index for varying control tube lengths L.

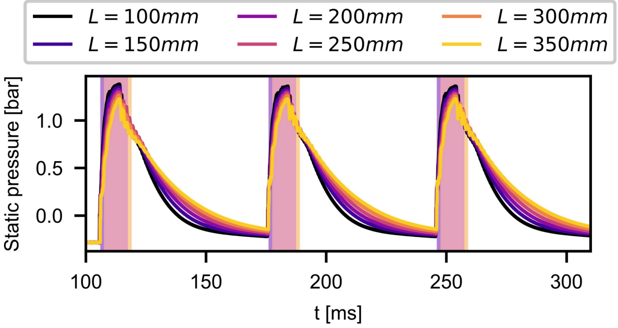

Figure 8: Pressure sensor time signal for varying control tube lengths L.

The data has been recorded in 20 sets of 20 consecutive pulses, in which the first pulse is generated by the transducer starting from its initial state, while the follow-up pulses are generated with limited regeneration time. Averaging only the individual follow-up pulses from the pulse trains acquired, the influence of τ on the individual pulses is investigated. Figure 5 shows that the first pulse of the pulse train has almost the same amplitude for all τ and that it is mostly the follow-up pulses that cause the mean US amplitude to drop for shorter regeneration times. This is especially the case for τ = 60 ms and τ = 80 ms.

Figure 6 shows the relation of p_{min} during the follow-up pulses to p_{min} of the first pulse. Since this relation is only negative when the signs of the pressure values differ, it gives an indication to what extent the flow reaches its initial state. Figure 6 shows that for τ = 60 ms the pressure does not fully return to negative values and reaches only 5% of the first pulse p_{min} for τ = 80 ms. This behavior indicates that the flow has not fully switched back to *off* state when setting these pulse separation times, which may cause the reduced US amplitude.

Tube length

The maximum US amplitude $\bar{a}$ is shown to be almost constant for all tube lengths investigated (figure 7). The SQI, however, is constantly increasing with increasing tube length, indicating lower flow noise during the transducer's *on* state. This behavior is believed to be caused by a decreased mass flow in the exiting air jet.

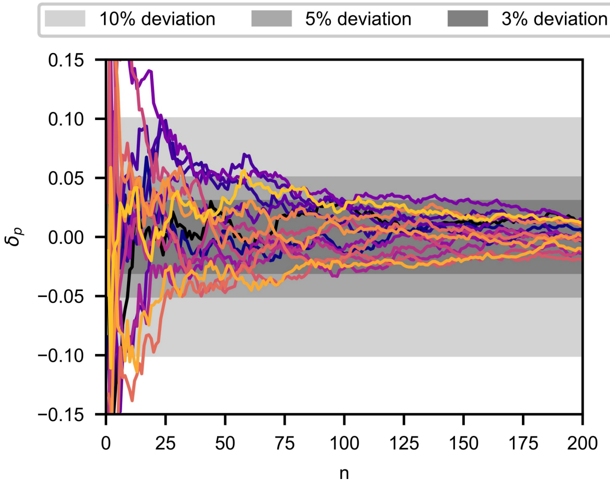

Figure 9: Convergence of all datasets measured.

The prolonged control tubing is not only stretching the pressure ramp due to its increased capacitance but also induces additional pressure loss in the system. This pressure loss in turn reduces the mass flow through the control ports, that are contributors of the overall exiting mass flow. Consequently, the increasing SQI has an inverse dependency of measured static pressure maximum, which is falling linearly as the tubing length is increased. A snippet of the the static pressure behavior for all tube lengths is given in figure 8. Beside the decreasing p_{max}, it also shows that p_{min} is increasing as longer tubing is used. While this has a negligible effect on $\bar{a}$ in the cases studied here, it likely impedes full switching if very long tubes are used, similar to the case of high reptition rates.

Convergence

The results presented in this study are extracted from a sample of 400 US pulses at each operating point. A major criterion for deciding on a parameter set to use in NDT applications is the mean US pressure amplitude of the fluidic transducer. To assess the validity of the mean amplitude, the convergence of $\bar{a}$ has been evaluated. Figure 9 shows the relative deviation of the mean peak amplitude δ_a as the number of pulses n averaged is successively increased to $N = 400$ pulses so that:

$$\delta_a = (\bar{a}_n - \bar{a}_N)/\bar{a}_N \tag{3}$$

with $\bar{a}_N = \bar{a}$ from eq. 1.

While fluctuating for low n, all average deviations have converged to less than 10% deviation for $n \geq 24$ samples, less than 5% deviation for $n \geq 74$ samples, and less than 3% for $n \geq 165$ samples.

Conclusion

Given the novelty of the fluidic transducer, there is little information published on the parameters influencing amplitude and quality of the ultrasonic signal generated. Thus, the effects of repetition rate and control tube length of the transducer have been studied experimentally. It was shown that the repetition rate has a large impact on the ultrasound generation as high repetition frequencies leave the system not enough time to return to its initial state. In this case, the switching process remains incomplete, resulting in reduced ultrasonic amplitudes. While longer tubing also increases the regeneration time needed, this influence is small in all cases investigated, but is expected to increase for much longer tube lengths. Furthermore, the signal quality is improved by longer tubing, as the total mass flow in the tranducer's *on* state is reduced, resulting in flow noise reduction. Since the signal peak amplitudes vary significantly, the results are based on an average of a large number of individual pulses, which has been shown to converge.

Funding: This work was supported by the German Federal Ministry of Economics and Technology (BMWi) under the ZIM (Zentrales Innovationsprogramm Mittelstand) Grant No. ZF4044222WM7.

References

[1] Krautkrämer, J. and Krautkrämer, H.: Ultrasonic Testing of Materials, Springer Berlin Heidelberg, Berlin, Heidelberg, 1983, doi: 10.1007/978-3-662-02357-0

[2] Klinger, C. and Bettge, D.: Axle fracture of an ICE3 high speed train, Engineering Failure Analysis 35 (2013), 66-81, doi: 10.1016/j.engfailanal.2012.11.008

[3] Maev, R. G. *et al.*: Review of Advanced Acoustical Imaging Techniques for Nondestructive Evaluation of Art Objects, Res. Nondestruct. Evaluation 17 (2006), 191-204, doi: 10.1080/09349840600981088

[4] Gräfe, B.: Luftgekoppeltes Ultraschallecho-Verfahren für Betonbauteile, PhD Thesis, Technische Universität Berlin, Berlin, 2009, doi: 10.14279/depositonce-1964

[5] Bühling, B. *et al.*: Experimental analysis of the acoustic field of an ultrasonic pulse induced by a fluidic switch, J. Acous. Soc. Am. 149 (2021), 2150-2158, doi: 10.1121/10.0003937

[6] Rechten, A. W.: Fluidik: Grundlagen, Bauelemente, Schaltungen, Springer Berlin Heidelberg, 1976, doi: 10.1007/978-3-642-93042-3

[7] Warren, R. W.: Some parameters affecting the design of bistable fluid amplifiers, Proc. ASME Symp. Fluid Jet Control Devices, New York, 1962, 75-82.

[8] Lush, P. A.: Investigation of the switching mechanism in a large scale model of a turbulent reattachment amplifier, Proc. Second Cranfield Fluidics Conf., Cambridge, 1967, Paper A1

[9] Epstein, M.: Theoretical Investigation of the Switching Mechanism in a Bistable Wall Attachment Fluid Amplifier, J. Basic Eng. 93 (1971), 55-62, doi: 10.1115/1.3425182

[10] Thompson, R. V.: Supersonic fluidics: Empirical design data, Proc. Fourth Cranfield Fluidics Conf., vol. 2, Coventry, 1970, Paper N2

[11] Peng, J.-M. *et al.*: Effect of geometric parameters of the bistable fluidic amplifier in the liquid-jet hammer on its threshold flow velocity, Comput. Fluids 82 (2013), 38-49, doi: 10.1016/j.compfluid.2013.05.002

[12] Tesař, V.: No-moving-part valve for automatic flow switching, Chem. Eng. J. 162 (2010), 278-295, doi: 10.1016/j.cej.2010.04.028

[13] Schweitzer, T. *et al.*: Switching Action of a Bistable Fluidic Amplifier for Ultrasonic Testing, Fluids 6 (2021), 171, doi: 10.3390/fluids6050171