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INTERDIGITAL TRANSDUCERS FOR LAMB-WAVE BASED SHM SYSTEMS: DESIGN AND SENSITIVITY ANALYSIS

SUMMARY

Structural health monitoring (SHM) systems have been constantly improved in the past decades. Sensors for SHM should be built-in to perform continuous measurements in opposite to non-destructive testing (NDT), in case of which sensors have to be mounted on the structure only during measurements. One of the most promising type of the transducers dedicated for SHM systems is Interdigital Transducer (IDT), which is designed for ultrasonic Lamb wave monitoring. Mode selectivity, high excitation strength, wave directivity, small size and relatively low cost are the most important advantages of the IDT.

In the paper a designing process of the IDT is presented. Then, the results of numerical simulations and sensitivity analysis are discussed for exemplary IDT configuration.

***Keywords**: Lamb waves, System Health Monitoring, transducer, interdigital transducer*

PRZETWORNIKI IDT DLA SYSTEMÓW MONITOROWANIA STANU KONSTRUKCJI Z ZASTOSOWANIEM FAL LAMBA: PROJEKTOWANIE I ANALIZA WRAŻLIWOŚCI

Systemy monitorowania stanu konstrukcji (SHM) w ostatnich latach są dynamicznie rozwijane. Przetworniki wykorzystywane w tego typu systemach są na stałe montowane na badanej konstrukcji pozwalając na ciągły pomiar zmian jest stanu. Jednym z przetworników stosowanych w systemach SHM bazujących na powierzchniowych falach ultradźwiękowych są przetworniki międzypalczaste (IDT). Ich głównymi zaletami są małe rozmiary oraz zdolność do generowania wąskopasmowej fali kierunkowej o stosunkowo wysokiej amplitudzie.

W artykule przedstawiony został proces projektowania przetworników IDT. Omówiono wyniki przeprowadzonych symulacji oraz procesu analizy wrażliwości dla przedstawionej konstrukcji.

***Słowa kluczowe**: fale Lamba, systemy monitorowania stanu konstrukcji, przetworniki międzypalczaste, IDT*

1. INTRODUCTION

Recently non-destructive testing and structural health monitoring systems have been intensively developed. Among different techniques used for NDT and SHM, methods which are based on the ultrasonic waves are very promising (Raghavan and Cesnik 2007). Plate waves, also known as Lamb waves are the ultrasonic guided waves that can propagate in thin plates with parallel free boundaries. They may travel over a long distances even in materials with high attenuation ratio (Culshaw *et al*. 1998). Moreover, Lamb waves make it possible to examine the entire cross section of a planar structure and they can interfere with different types of defects (Rose 2002).

2. INTERDIGITAL TRANSDUCERS

Interdigital transducers are relatively novel constructions in NDT and SHM (Mamishev *et al*. 2004, White and Voltmer 1965), however the idea of the interdigital electrodes was born in the XIX-th century. A Typical IDT transducer is built of three main layers: bottom (ground) electrode, piezoelectric layer (substrate) and top (phase) electrodes (Fig. 1)

Bottom electrode is usually designed as a plate that covers almost the whole bottom surface of the transducer. Piezoelectric layer may be made of different materials: piezoelectric polymer (i.e.: PVDF (Bellan *et al*. 2005, Capineri *et al*. 2002, Wilcox *et al*. 1998)), piezoceramics (Luginbuhl

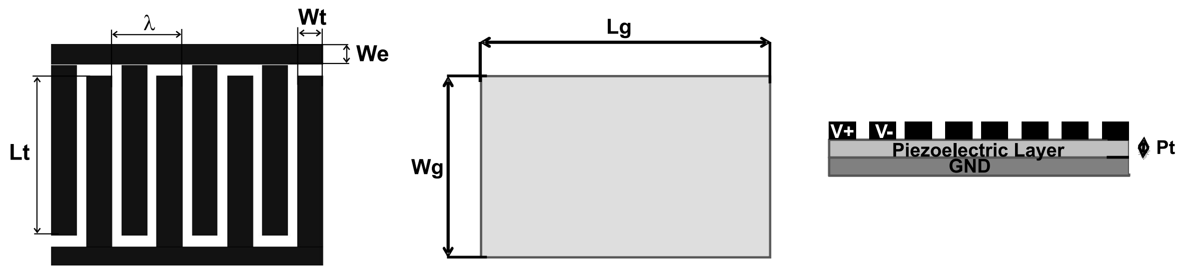

Fig. 1. Structure of the IDT transducer

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et al. 1997) or piezoceramic composites (i.e.: MFC (Williams *et al.* 2002)). The layer type determines different properties of the transducer like its elasticity, maximal power or frequency of the generated waves. Top electrodes of the IDT have the comb shape. The distance between the phase electrodes (finger spacing) determines the length of the induced wave (Monkhouse *et al.* 1997, 2000).

Other advantage of the IDT transducers, besides their modal selectivity, is the ability to generate waves as directional beams (Na *et al.* 2008, 2010). Generated beams propagate in the direction perpendicular to the electrode fingers while the divergence angle depends on the finger length.

2.1. Design of the IDT

The transducer presented in this paper is designed to excite the A0 mode in a 4mm-thick aluminum plate. This mode exists at a wide range of the frequencies but the most interesting are frequencies characterized by low dispersion i.e.: the frequency band for which the excited waves travel with approximately the same speed. This situation occurs at the maximum of the group velocity for the desired mode on the dispersion plot. Based on the analytically created dispersion plots (Fig. 2 and 3), group velocity of the A0 mode for 4mm-thick aluminum plate has been identified at 329 kHz (Fig. 2) and chosen for further investigation.

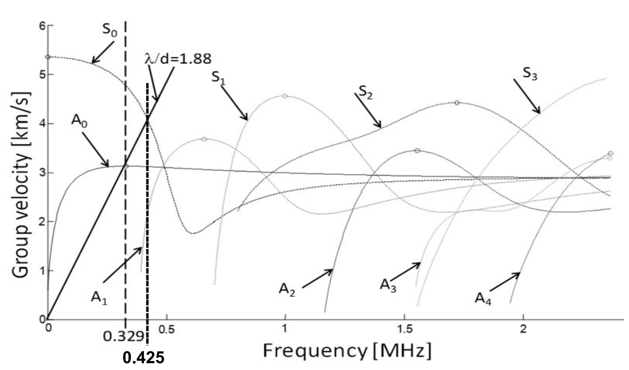

Fig. 2. Group velocity for a 4 mm aluminum plate

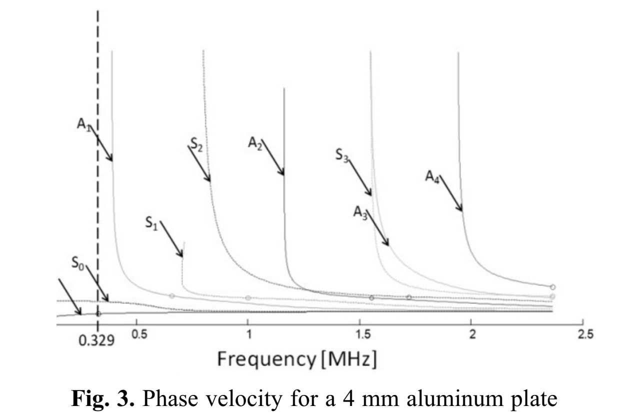

Fig. 3. Phase velocity for a 4 mm aluminum plate

Wavelength of the Lamb wave is calculated according to the equation:

$$\lambda = \frac{C_p}{f} \tag{1}$$

where C_p is the phase velocity and f is the frequency. Phase velocity for the given frequency may be read from dispersion curves plots (Fig. 3). For the presented example the wavelength equals:

$$\lambda = \frac{2\,468\,000 \text{ mm/s}}{329\,000 \text{ Hz}} = 7.5 \text{ mm}$$

2.2. Influence of geometrical parameters of the IDT on the amplitude and shape of generated waves

Only some of the IDT geometrical parameters may be calculated directly using analytical formulas i.e.: electrode length (*LT*), wavelength/electrode spacing (λ). Other parameters like piezoelectric layer thickness or electrode dimensions may be adjusted without influence on the wave frequency or divergence angle.

To determine the influence of these parameters on the overall performance of the transducer a sensitivity analysis has been performed. There have been carried out numerical simulations for the following cases (Tab. 1) assuming:

- Nominal dimensions of the transducer.
- Change of the piezoelectric layer thickness (PT).
- Change of the ground electrode width (WG).
- Change of the side electrode width (WE).
- Change of the tooth electrode width (WT).
- Change of the tooth electrode length (LT).

Numerical model of the IDT located in the centre of the 4mm-thick aluminum plate was created in the ANSYS Multiphysics software. The size of the plate was assumed as 500×500 mm. The model was built using 20-node brick-type finite elements. Fully coupled transient analyses were performed to simulate the piezoelectric effect in the transducer.

Table 1

Parameters of the IDT transducer used for sensitivity analysis

	PT [mm]		WG [mm]		WE [mm]		WT [mm]		LT [mm]	
Nominal value	0.5		15		1.5		1.9		15	
Allowed values	0.3	0.75	12	18	0.75	3	1.3	2.4	12	18

All simulations were performed with the same settings: a five-cycle tone burst modulated with Hanning window with amplitude $50V_{p\text{-}p}$ was used as an excitation signal and simulation time was equal 80 μs. Excitation signal in the time domain and its frequency spectrum are presented in the Figures 4 and 5 respectively.

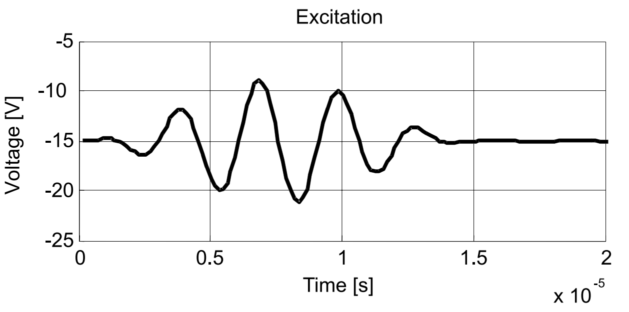

Fig. 4. Excitation signal

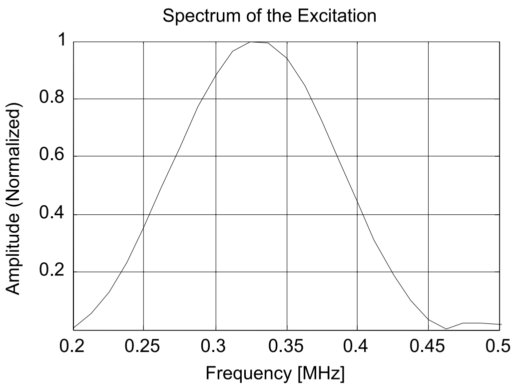

Fig. 5. FFT of the excitation signal

During simulations two measurement points were located on the plate at the distance of 150 mm from the center of the plate one in the X-direction (node 2 – perpendicular to the finger electrodes) and the second in the Y-direction (node 4 – parallel to the tooth electrodes) (Fig. 6).

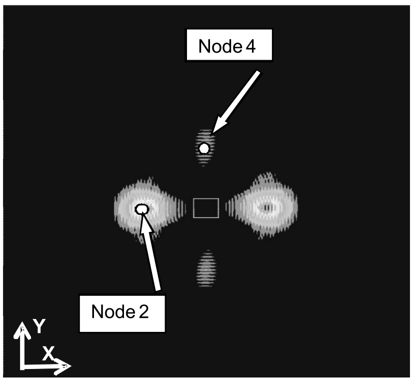

Fig. 6. Localizations of the measuring points during simulations

To compare the amplitudes in both points the simulations with nominal transducer parameters were performed (Tab. 1). Data acquired in simulations is presented in Figures 7–8.

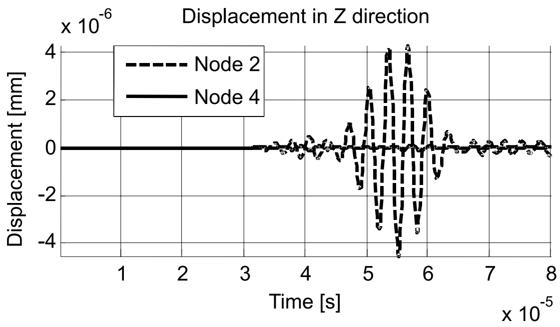

Fig. 7. Out of plane displacements acquired during simulations at Node 2 and Node 4

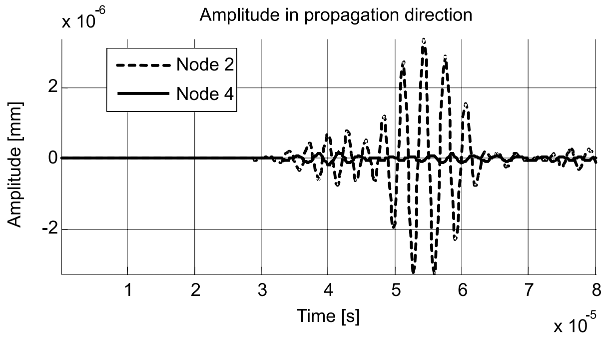

Fig. 8. In plane displacements acquired during simulations in Node 2 and Node 4

At both points (amplitude in the Z direction and amplitude in the propagation direction (X for Node 2 and Y for Node 4)) the amplitude of the generated wave is ten times lower in Node 4 than in Node 2. Therefore, for the further analysis, only data from the Node 2 has been used.

2.3. Results of the sensitivity analysis

The sensitivity analyses have been performed to determine the influence of all defined input variables (Tab. 1) on the parameters of generated waves. As an example, there is presented the influence of the changes in the PZT layer thickness (PT) on the displacement amplitude, shown in Figure 9.

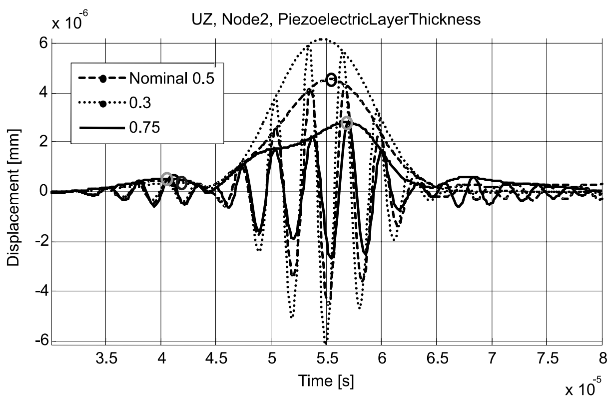

Fig. 9. Wave generated by IDT transducer; the changes in the PZT thickness (PT) considered

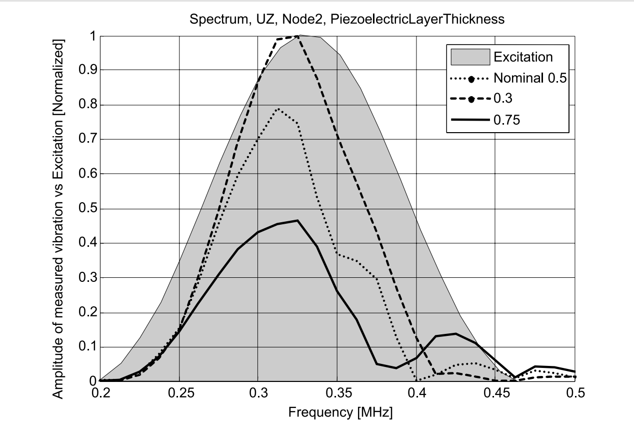

Fig. 10. Frequency range of generated waves

The changes in frequency spectrum, also compared to the excitation spectrum, are presented in Figure 10. It can be noticed that on the frequency plot there are additional peaks besides one which is related to the mode A0. Analysis of the dispersion plots (Fig. 2) shows that for the excitation frequency 329 kHz two modes (both A0 and S0), characterizing different group velocities, are generated. Moreover, additional S0 mode at 425 kHz related to the teeth spacing is generated. The dispersive character of the S0 modes is the main source of distortions observed on the frequency plots.

Carried out sensitivity analysis has allowed to estimate the influence of design parameters (which are listed in Tab. 1) on A0 and S0 amplitudes as well as on the A0/S0 ratio. The changes in the amplitude of both A0 and S0 wave mode depending on the values of design parameters are presented in Figures 11 and 12.

Based on these results, the normalized sensitivities S have been calculated according to the equation:

$$S_{V,n} = \frac{V(\max(P_n)) - V(\min(P_n))}{V_{NOM}} \cdot 100\,[\%] \qquad (2)$$

where:

V – denotes A0, S0 amplitude or A0/S0 amplitude ratio respectively,

P_n – design parameter ($1 \le n \le 5$), which subsequently stands for: PT, WG, WE, WT, LT,

V_{NOM} – amplitude of V for nominal design.

Calculated sensitivities are presented in Figures 13–14 and Tables 2–3.

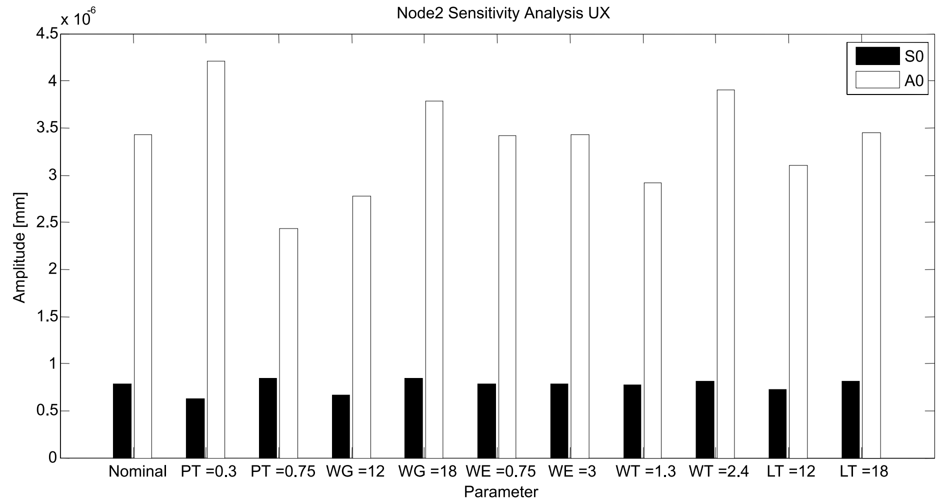

Fig. 11. Comparison of A0 and S0 amplitudes obtained by numerical simulations in Node 2 for X direction

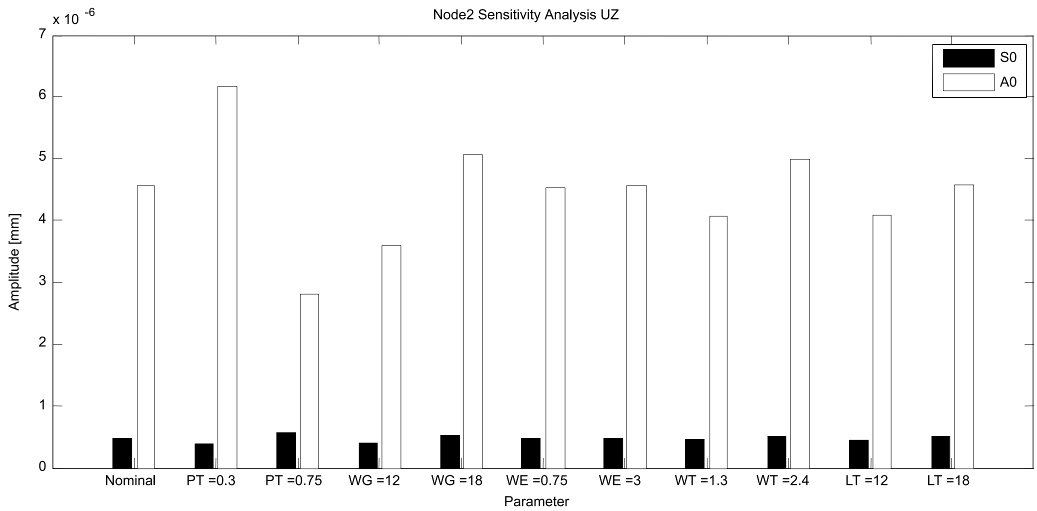

Fig. 12. Comparison of A0 and S0 amplitudes obtained by numerical simulations in Node 2 for Z direction

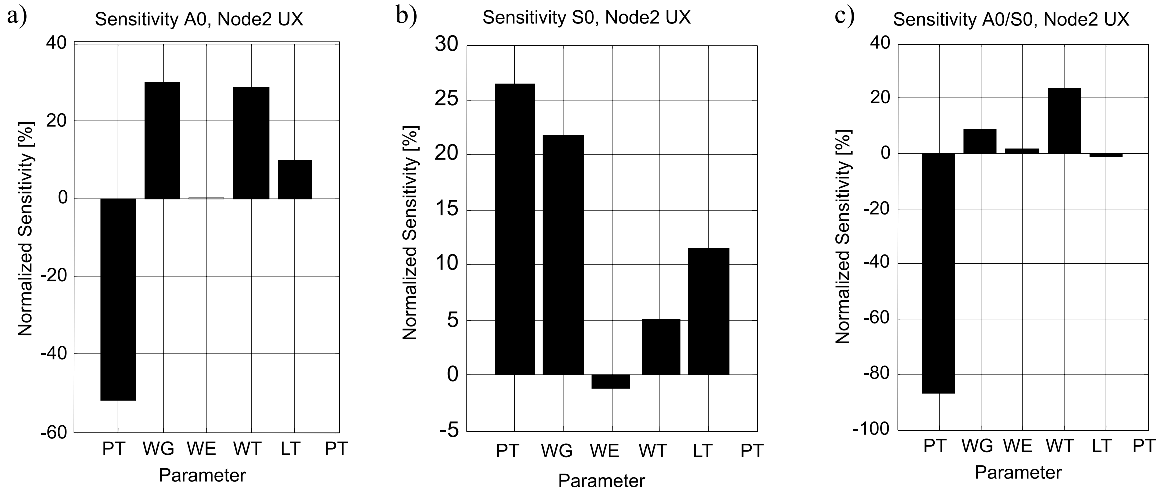

Fig. 13. Normalized sensitivities for X direction: a) A0 sensitivity; b) S0 sensitivity; c) S0/A0 sensitivity

Table 2

Normalized sensitivities for X direction

	PT	WG	WE	WT	LT
A0	–51.7%	29.8%	0.36%	28.6%	10%
S0	26.4%	21.7%	–1.08%	5.1%	11.5%
A0/S0	–86.6%	8.71%	1.45%	23.3%	–1.37%

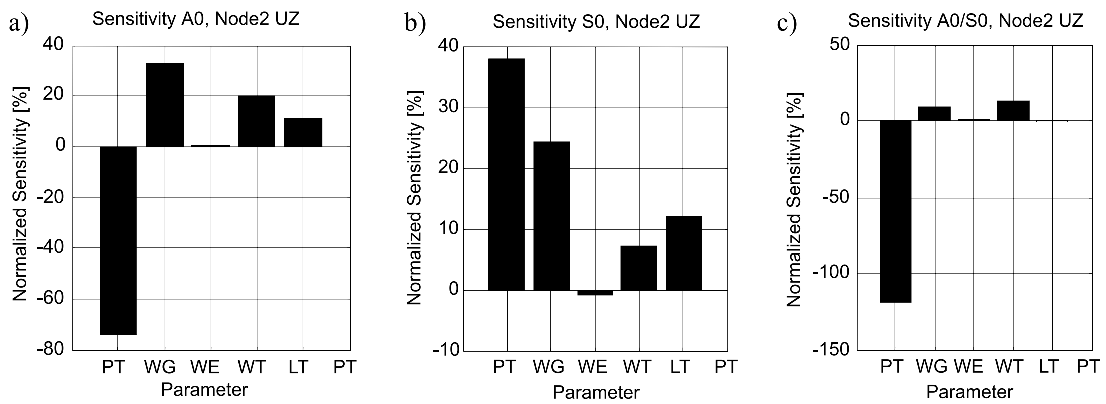

Fig. 14. Normalized sensitivities for Z direction: a) A0 sensitivity; b) S0 sensitivity; c) A0/S0 sensitivity

Table 3

Normalized sensitivities for Z direction

	PT	WG	WE	WT	LT
A0	–73.5%	32.5%	0.32%	20.2%	10.7%
S0	37.9%	24.2%	–0.86%	6.95%	11.8%
A0/S0	–119.6%	8.96%	1.19%	13.3%	–1.03%

Based on the calculated sensitivities it can be noticed that the most influential parameter is the piezoelectric layer thickness. In both directions (X, Z) the reduction of the transducer thickness results in the increase of the amplitude of generated A0 wave ($S_{A0,PT,X}$ = –51.7%, $S_{A0,PT,Z}$ = –73.5%) and reduction of S0 amplitude ($S_{S0,PT,X}$ = = 26.4%, $S_{S0,PT,Z}$ = 37.9%). To increase the A0/S0 amplitude ratio ($S_{A0/S0,PT,X}$ = –86.6%, $S_{A0/S0,PT,Z}$ = –119.6%) the thickness of the piezoelectric layer should be reduced. However it should be done within limited range only as it results in deterioration of the mechanical strength of the transducer.

The width of interdigital electrode has also a significant influence on the A0/S0 ratio ($S_{A0/S0,WT,X}$ = 23.3%, $S_{A0/S0,WT,Z}$ = 13.3%). In this case amplitudes of both A0 and S0 modes ($S_{A0,WT,X}$ = 28.6%, $S_{A0,WT,Z}$ = 20.2%, $S_{S0,PT,X}$ = 5.1%, $S_{S0,PT,Z}$ = 6.95%) are increased. The only limitation of the increase of mentioned width is the length of desired wave λ (i.e.: the distance between teeth).

The width of ground electrode has even higher influence on the amplitude of generated A0 mode ($S_{A0,WG,X}$ = 29.8%, $S_{A0,WG,Z}$ = 32.5%) but it has similar influence on the S0 mode ($S_{S0,PT,X}$ = 21.7%, $S_{S0,PT,Z}$ = 24.2%). Finally this leads to much lower influence on the A0/S0 ratio ($S_{A0/S0,WT,X}$ = = 8.71%, $S_{A0/S0,WT,Z}$ = 8.96%) than the influence of the width of interdigital electrode.

3. CONCLUSIONS

The interdigital transducers are novel constructions in SHM. The paper concerns an exemplary design process carried out for IDT. Numerical experiments have confirmed that presented transducer characterizes required modal selectivity and directivity of beam pattern. The results of sensitivity analyses indicate which parameters have the greatest influence on the IDT's modal selectivity.

During further work the optimization of the transducer design process is planned to be performed on the basis of sensitivity analysis. Optimized IDT will be manufactured and tested on the laboratory test rigs and real-life objects.

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