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Investigation of phased arrays for guided waves applications

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Abstract

One of the main problems in a long-range ultrasonics is effective generation of a desired wave mode. The objective of this paper is investigation and optimisation of low frequency transducer arrays for excitation of Lamb waves for long-range ultrasonics applications. The different types and parameters of transducer arrays have been investigated. The investigations were performed using the finite difference method. The dependence of the generated signal amplitude versus the gap between elements has been determined. It was shown that most optimal distance is $\lambda/4$, where λ is the wavelength, but the delay time should be optimised for each particular case. It was demonstrated, that the optimal delay time between excitation instants of the array elements enables to increase efficiency of excitation.

Keywords: ultrasonic, transducer array, guided waves, simulation

Introduction

Non-destructive testing NDT of large engineering constructions with a size 10 and more meters is problematic. Such objects are wind power stations, bridge constructions and underground pipes. The guided ultrasonic waves are very attractive for testing these objects because they propagates long distances inside the object and enables at once to test big segments of the construction [3, 4, 6]. The guided waves are dispersive and multimode. Most important question in the application of guided waves is optimal excitation of a desired wave mode at the selected frequency. In practice mainly symmetrical S_0 and asymmetrical A_0 wave modes are used.

The frequency range used in a long-range ultrasonics usually is 20-300 kHz. At these frequencies the wavelengths of guided waves λ are approximately in the range of tens of centimetres. In this cases excitation of waves using a single transducer is not efficient, because such transducer operates as a point source in comparison to the wavelength and the directivity of generated waves is very weak.

Much more promising is application of transducer arrays. In conventional transducer arrays, the distance between elements is usually selected equal to $\lambda/2$, but such a distance is not practical for guided waves because array dimensions will be several meters. Furthermore, these dimensions complicate construction of the array and the attachments to the object. Therefore, the objective of the presented work was minimisation of array dimensions and optimization of the excitation efficiency of S_0 guided wave mode.

Object

Efficiency of transducer arrays depends on the number of elements in the array and spacing between elements [1, 2]. For excitation and reception of guided Lamb waves in plates, two types of arrays may be used - one-side (Fig.1) and two-side arrays (Fig.2). In the first case array elements are attached only to one surface of the plate. In the second case array elements are attached symmetrically from both sides. In each type of array, the array elements may excite or longitudinal displacement in a plate (along the length of the plate), or transversal – across the plate. Longitudinal displacements may be excited using SH mode array elements, the transversal displacements – longitudinal (L) mode transducers.

In this paper both types – one-side and two-side array were simulated. The investigation was performed using the finite difference method in 2D approach (Wave2000). The efficiency of excitation of the S_0 Lamb wave modes in a 40 mm unbounded steel plate was investigated. The set up of numerical experiments is presented in Fig.1 and 2.

The length of the plate along x axis is 14 meters. Such a length along x axis was selected in order to avoid at the receiver the interference of the direct waves and the waves reflected by the ends of the plate. The plate is infinite in y axis direction. It was assumed that the steel plate is unloaded, e.g. is placed in vacuum. The transducer array elements were situated along x axis with some distances d from each other. The width a of each element was 10 mm. The first transducer array element is placed at the centre of the model.

The transmitting transducer array elements were simulated as initial boundary conditions, e.g. a predefined time dependent displacement. This means that all spatial discretization nodes inside the area of a single array element "vibrates" identically, corresponding to the waveform of the excitation signal and are not affected by propagating waves. Therefore, such "virtual" array elements possess an infinite bandwidth and can excite longitudinal or shear component depending on a selected option. Virtual receiver was placed at 3 meters from the first array element and can pick up longitudinal and transversal (shear) displacement components of ultrasound wave. The virtual receiver is transparent for any type of displacements and does not affect propagating waves, e.g. does not create reflected waves.

Selection of excitation frequency and signal parameters

The calculated dispersion curves of the phase velocity in a 40 mm thickness steel plate are presented in Fig. 3.

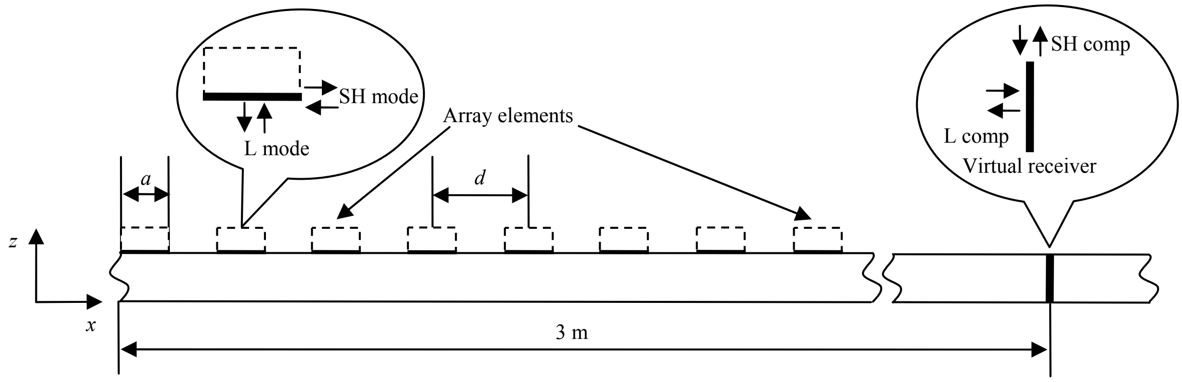

Fig. 1. **The array elements of the modelled one side transducer array**

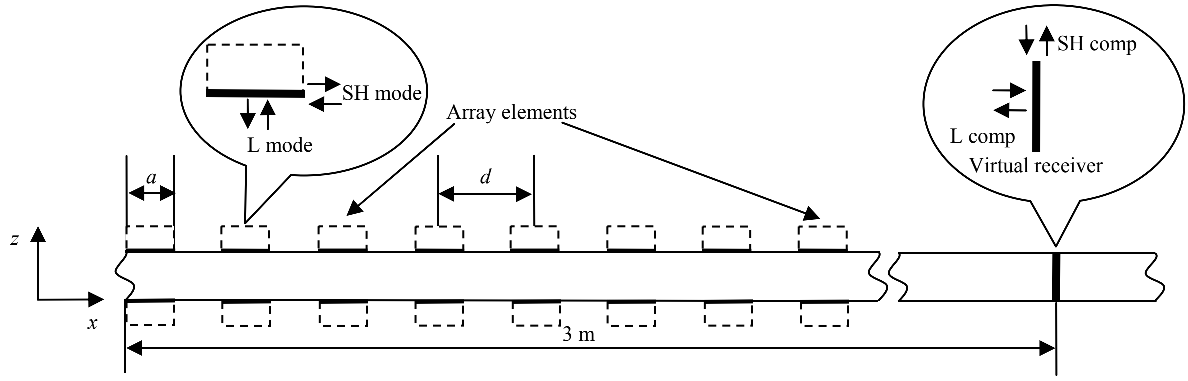

Fig. 2**. The array of elements of the modelled two side transducer array**

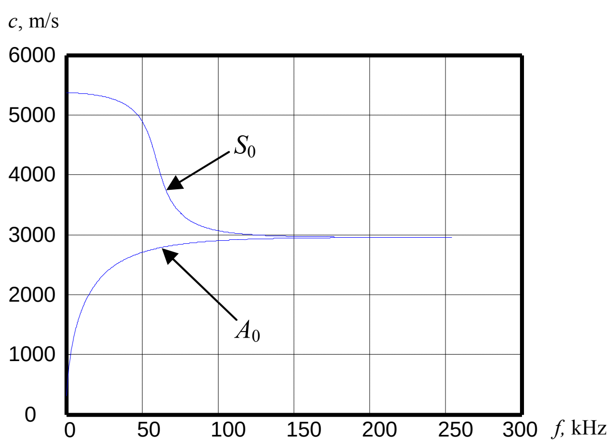

Fig.3. **The dispersion curves of phase velocity Lamb waves in a 40 mm thickness steel plate**

From the presented dispersion curves follows that in order to avoid strong effect of dispersion the frequency of S_0 and A_0 modes should be selected in the range from 10 kHz to 40 kHz. In this frequency range the signals of S_0 and A_0 Lamb wave modes may be simply separated in the time domain.

The numerical simulation was performed at the frequency 30 kHz. The bulk ultrasound velocity in a steel is approximately 5900 m/s. The velocity of the S_0 Lamb wave mode in a steel plate with the thickness 40 mm at 30 kHz according to dispersion curves is 5272 m/s.

The wavelength of the S_0 mode at this frequency is $\lambda = 0.176$ m. The excitation have been performed using 5 periods burst with Gaussian envelope. The waveform of the excitation signal is presented in Fig.4.

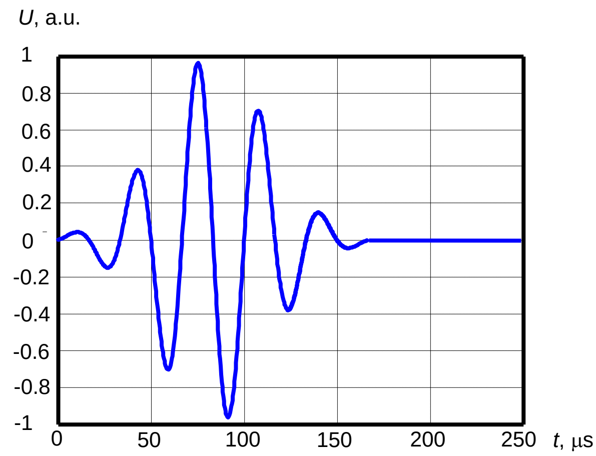

Fig.4. **30 kHz excitation impulse with the Gaussian envelope**

Simulation and results

Simulation was carried out using grid with the 2 mm step in the space domain. Integration step in the time domain was 0.2831 µs. The arrays with the distances $d=\lambda/2$; $\lambda/4$; $\lambda/8$ between elements were investigated. The delay time between arrays elements were selected as

$\Delta\tau_n = (n-1)\cdot\frac{d_E}{c_L}$ where $(n = 1,...N)$ is the number of element, d_E is the distance between elements, c_L is the longitudinal wave velocity in a plate. The dependencies of the used delay times between array elements versus the number of an element are presented in Fig.5.

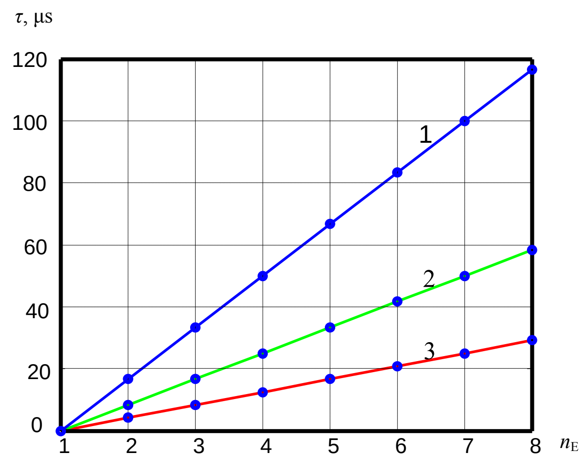

Fig. 5. **The theoretical excitation delay times of different array elements at different distances between elements: 1 - λ/2, 2 - λ/4, 3 - λ/8**

The investigations were performed using the shear mode transducers array. Only the longitudinal displacement component of S_0 mode of Lamb wave was registered (see Fig.1 and 2). The peak-to-peak amplitude of each recorded signal was determined. The obtained dependencies for one side transducer array with different distances, between elements are presented in Fig.6.

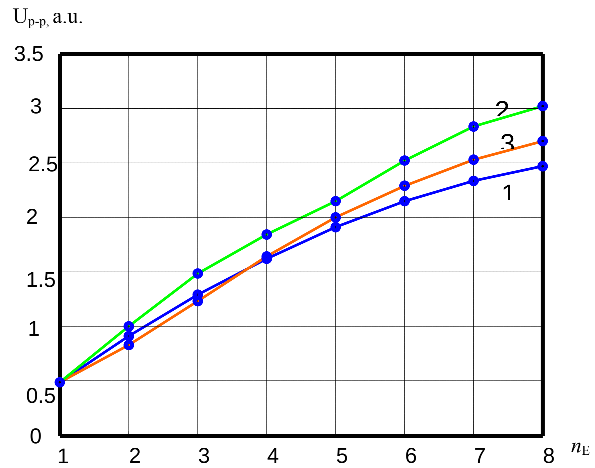

Fig. 6. **The peak to peak amplitude of the transmitted Lamb wave generated with the one side array versus number of excited elements (delay time between elements is linear, the distance between elements: 1 - λ/2, 2 - λ/4, 3 - λ/8**.

The obtained results indicate, that the of the excited S_o mode amplitude is increasing, but not proportionally to the number of element. Therefore, this phenomenon may be called as a saturation. The optimal spacing between elements in this case is λ/4. The results obtained by the two side array have a different character (Fig.7). From the results presented follows that when there are more elements than 3 the excited signals amplitudes are not increasing, but decreasing. It means that between excitation delay time instants of array elements is not correct.

For a better understanding of this phenomenon a more detailed investigation was carried out.

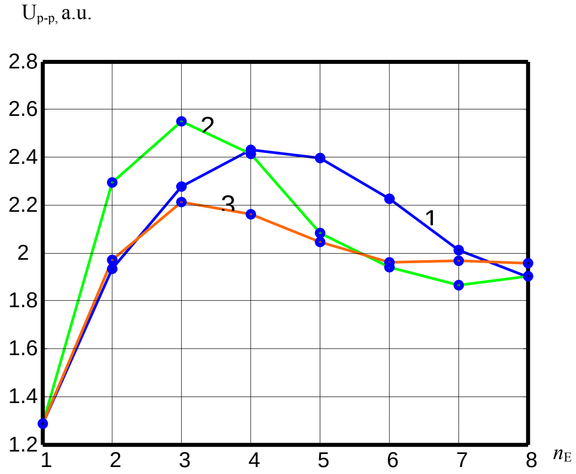

Fig. 7. **The peak to peak amplitude of the transmitted Lamb wave generated by the two side array versus number of excited elements (delay time between elements is linear, the distance between elements: 1 - λ/2, 2 - λ/4, 3 - λ/8.**

Why the amplitude is not increasing proportionally to the number of elements in the array? In order to answer this question we have to return to the array excitation principle shown in Fig.8.

Each element were excited using the individual delay time. This delay time $\Delta\tau_n$ is selected in such a way that the acoustical displacements $u_n(t)$, $(n = 1,...N)$ of each transmitter after superposition gives a maximal amplitude. The resulting signal after superposition is given by:

$$u_\Sigma(t) = u_1(t_0) + u_2(t_0 - \Delta\tau_1) + ... + u_8(t_0 - \Delta\tau_7) = \sum_{n=0}^{N} u_n(t - \Delta\tau_n). \quad (1)$$

The phases of partial waves, generated by a different array elements depend on a spatial position of a transmitting element and phase velocity of the particular Lamb wave mode. From the numerical modelling it was found that in the regions where boundary conditions simulate excitation by an applied force, the phase velocity is different from the regions with free boundary conditions.

In order to overcome this problem we propose an alternative array excitation method in which the delay time between excitation instants of different array elements is corrected according to different phase velocity.

The optimal excitation is obtained in the case when the excited signals of different array elements are added in phase. In order to determine the actual wave propagation time between adjacent array elements, the cross-correlation method was used. For determination of the optimal delay times different transducer array elements were excited separately and the signals were recorded at the analyzed distance.

The set of signals was obtained from which the optimal delay times were determined according to

$$\Delta\tau_n^{Opt} = \arg\{\max[\mathrm{CCF}(u_1(t), u_{n-1}(t))]\}, \quad (2)$$

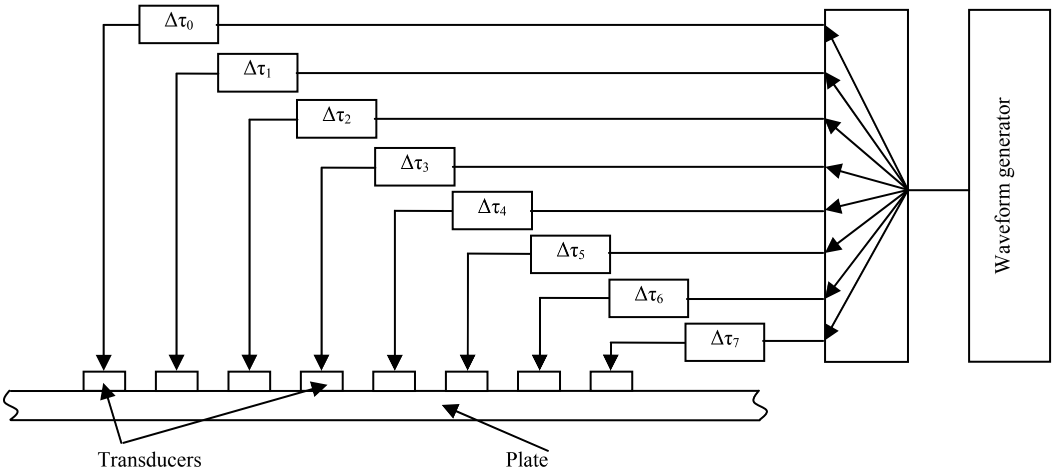

Fig.8. **Basic principle of Lamb wave array excitation. $\Delta\tau_n$ is the delay between array elements**

where CCF denotes Cross Correlation Function, $u_1(t)$ is signal from the first array element, $u_n(t)$ is the signal generated by the n-th element.

The obtained excitation delays are presented in Fig.9 and 11. Please note the dependency of the new element delay times versus element number is nonlinear. Also some particular time hop may be observed which is caused by amplitude shift one period of the signal.

The results obtained using these new calculated delay times are presented in Fig.10 and 12.

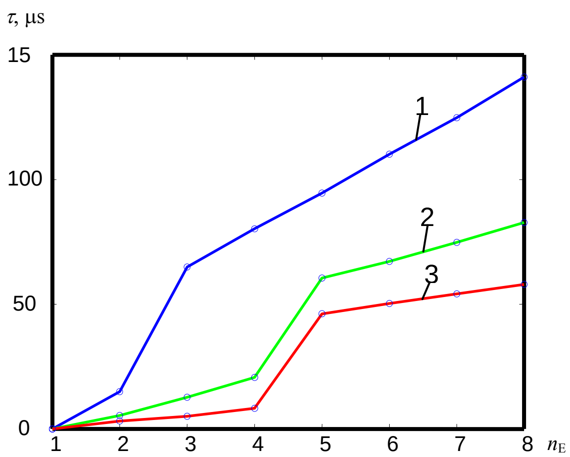

Fig. 9. **Measured excitation delay time of different elements excited in a shear mode of one-sided transducer array: 1 - λ/2; 2 - λ/4; 3 - λ/8**.

From the results presented in Fig.10 and 12 follows that after correction of the excitation instants of the array elements almost a linear dependence of the excited Lamb wave amplitude versus number of elements in the array is obtained. Very essential improvement is observed in the case of the two-side array with the distance between elements $\lambda/4$. When the distance between elements is shorter, e.g. $\lambda/8$, the improvement is smaller, because the width of a particular element is comparable with the gap between elements.

In other words, in a short array ($d = \lambda/8$) elements are too wide in comparison to the whole array length. For the optimal excitation the phases of exciting signals should be different even inside the area of each array element.

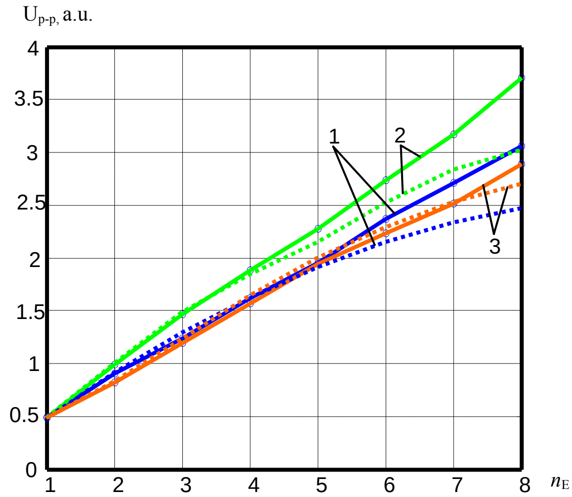

Fig.10. **The peak to peak amplitude of the transmitted Lamb wave generated with the one side array versus number of excited elements (delay time between elements is linear (dashed) and optimised, the distance between elements: 1 - λ/2, 2 - λ/4, 3 - λ/8.**

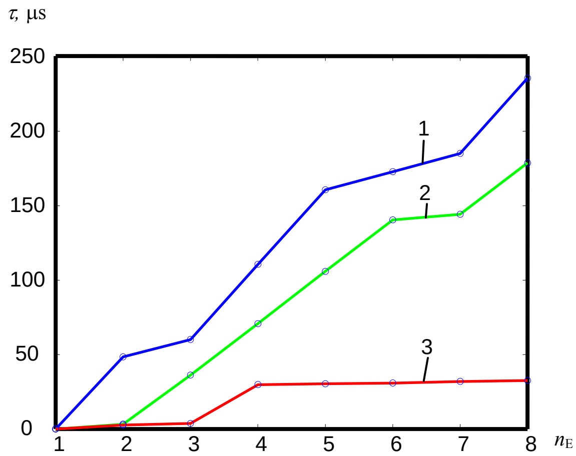

Fig.11. **Measured excitation delay time of different elements excited in a shear mode of two side transducer array: 1 - λ/2, 2 - λ/4, 3 - λ/8**

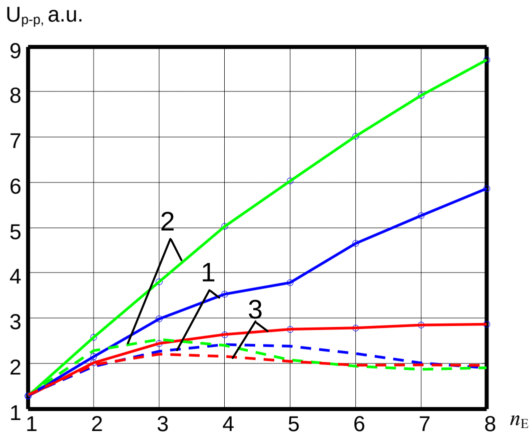

Fig.12. **The peak to peak amplitude of the transmitted Lamb wave generated with the two side array versus number of excited elements (delay time between elements is linear (dashed) and optimised, the distance between elements: 1 - λ/2, 2 - λ/4, 3 - λ/8.**

Discussions

The simulation results demonstrated that the delay time between array elements calculated using the Lamb wave propagation in an unloaded plate velocity is not optimal. This may be caused by the fact that the boundary conditions in this case are different comparing to the unloaded plate and as a consequence, this leads to the different guided wave propagation velocity. Additionally, each array element attached to the plate is an obstacle for propagating waves and reflection of guided waves from it takes place. So, the received at some distance signal is the result of the interference of the direct signal and the signals a few times reflected between transducer elements.

Of course these results were obtained using numerical modeling and they may differ from experimental ones. However, the numerical method, such as finite difference or finite element, if correctly used, represents correctly main regularities of wave propagation in a solid structure, at least, for linear acoustics. This was proved by many investigations carried out by different scientific groups. On the other hand, the most complicated parts in such a modeling are boundary conditions in the transducer attachment place or the wave excitation technique. In the investigations carried out the excitation was simulated as predetermined displacements at the transducer attachment place. This possibly does not coincide with the boundary conditions in real conditions. Nevertheless, it is known that any mechanical load in a limited area of the waveguide affects propagating guided waves, creating a partial reflection of them and mode conversion phenomena [5].

So, it can be stated that in experimental conditions probably the observed the regularities will not be identical to the simulated ones, but in any case the theoretically calculated delay time of transducer excitation which is linearly increasing with the number of the element in the array will not be optimal. The optimal delay times can be obtained only using the measured delay time between individual elements of the arrays. Taking into account existence of multiple modes of guided waves, the most promising for excitation and reception of necessary Lamb wave modes are transducer arrays with the adaptive excitation delay time.

Conclusions

The investigation carried out using modeling have shown that the used transducer array affects the parameters of the propagating under guided waves and this leads to the fact that the theoretically calculated excitation delay times between elements are not optimal.

The non-optimal selection of the excitation delay times does not enable to increase amplitude of the generated guided wave proportionally to the number transducer elements and some saturation or even reduction of the amplitude depending on the number of elements can be observed.

The optimal delay times should be determined experimentally by the delay time measurement of the each individual element of transducer arrays. This should be performed separately for each object under investigation, so the most promising for excitation of guided waves are adaptive transducer arrays.

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Fazuotųjų ultragarsinių gardelių nukreiptosioms bangoms žadinti tyrimas

Reziumė

Neardomiesiems bandymams naudojant nukreiptąsias ultragarsines bangas yra aktualu efektyvus pasirinktos modos sužadinimas. Šio darbo tikslas buvo ištirti ultragarsinių gardelių panaudojimo norimai nukreiptųjų bangų modai žadinti galimybes ir nustatyti optimalius gardelės valdymo parametrus. Buvo tiriamos vienpusės ir dvipusės ultragarsinės gardelės ir jų efektyvumo priklausomybė nuo atstumo tarp elementų, elementų skaičiaus ir fazavimo laiko. Tyrimai buvo atliekami naudojant modeliavimą baigtinių skirtumų metodu. Modeliavimo rezultatai parodė, kad įprastas tiesinis gardelės elementų fazavimas ne visuomet yra optimalus ir didinant gardelės elementų skaičių, žadinimo efektyvumas nedidėjo proporcingai elementų skaičiui. Kaip tyrimų rezultatas buvo pasiūlytas patobulintas fazavimo parametrų koregavimo metodas, pagrįstas individualiu kiekvieno gardelės elemento fazavimo laiko parinkimu pagal žadinimo modą ir tiriamąjį objektą.

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