https://doi.org/10.52326/jes.utm.2021.28(3).02
CZU 621.3.092.53:534.2

SETTING OF THE ANGLE OF INCIDENCE FOR GENERATING LAMB WAVES BY NON-CONTACT METHOD

Alexandru Buga*, ORCID ID: 0000-0002-4342-0502

Technical University of Moldova, 168 Ștefan cel Mare Blvd., MD-2004, Chișinău, Republic of Moldova
*Corresponding author: Alexandru Buga, *alexandru.buga@precesia.utm.md*

Received: 06. 17. 2021
Accepted: 08. 10. 2021

Abstract. The article examined the problem of the experimental setting of incidence angles for the generation of Lamb waves in plate-type parts by the non-contact ultrasonic control method. This type of control is mainly done by the use of two types of waves: Rayleigh, which detects invisible defects on the surface of parts, and Lamb waves mode A_0 and S_0. Mostly used is the mode A_0 due to the propagation over distances of interest in the tested materials. One of the primary aim during the testing process is to position the ultrasonic transducers (transmitter and receiver) at oblique angles of incidence on a surface. The transducers should be positioned on an access face of the plate, as is common in industrial practice, at a fixed distance from the measured plate, and leaving an air gap between transducers and the tested plate. The ultrasonic transducers are moved simultaneously linearly or in zigzag on the surface of the plate-type part to measure the hidden defects (cracks, pores, inclusions) that appear in the composite materials during the manufacturing process or during the operation. The presented work brings new insights into the setting of the angle of incidence for generating lamb waves by non-contact method.

Keywords: *non-contact ultrasonic control, invisible defects measurement, Lamb waves, ultrasonic transducers, angle of incidence.*

Introduction

First applications of composite materials in the automotive industry were those in the field of car bodies manufacturing: in 1953 the body of the Corvette Chevrolet (USA) was entirely made of glass-epoxy; in 1968 the rims of the Citroen SM were made of epoxy glass; in 1970 - the bumper of the Renault R5 was made of epoxy glass; in 1980 John Barnard, an engineer in the McLaren Formula 1 team, built the first carbon Kevlar chassis and from other composite materials; in 2002 the body of the McLaren Mercedes SLR series car was made entirely of carbon fiber. As regarding to the use of composite materials in the aircraft manufacturing industry, it is worth mentioning the Boeing 787 Dreamliner passenger plane, which was made of the following materials: 50% - composite materials based on carbon fiber, 20% - aluminum, 15% - titanium, 10% - steel, and 5% other materials [1]. Composite materials are also widely used in the aerospace industry, such as the thermal shield of the HERMES spacecraft (*Heliophysics Environmental and Radiation Measurement Experiment Suite)* which "tiles" are composed of composites, based on reinforcements of carbon fibers and matrices of silicon carbide (called C/SiC or C/C-SiC composites). This heat shield resists to at least thirty landings [2].

Main advantages of composite materials are economic and qualitative aspects because the use of these materials allow saving significant amounts of expensive and traditional materials, the latter once becoming deficient. Herein, composite materials demonstrate continuously improving quality and increased duration of operation in conditions of high performance [3]. Therefore, for industrialized countries composite materials represent a priority area, occupying the forefront of the continuous process of technological innovation in the construction of cars, planes, ships due to mechanical strength and rigidity (increased tensile strength *Rm*, Kevlar composite has *Rm* twice larger than glass), resistance to corrosion, chemical agents and high temperatures (ex. Kevlar, Teflon up to 500^{0}C, and ceramic fibers such as SiC, Si_3N_4, and Al_2O_3 between 1400^{0}C and 2000^{0}C). Low density (composites with epoxy resins reinforced with Si, B, C fibers, have a density less than 2 g/cm^3), dimensional stability (low coefficient of thermal expansion), resistance to variable stress and wear and high durability in operation (under the same operating conditions 1 kg of Kevlar replaces 5 kg of steel, at an equal service life) represent other important advantages of composite materials [4].

Previously published researches showed different methods to test composite and non-composite materials. For instances, there has been widely described non-contact ultrasonic control but without mentioning about angle of incidence for generating Lamb waves [5, 6]. The study conducted by Gheorghe I. Gheorghe et al (2011) showed the practical application of the Intelligent Mechatronic Equipment for dimensional control of non-composite materials [7, 8]. Others published the results of another type of mechatronic equipment use for the tightness checking of non-composite materials [9]. However, these methods are not reliable due to easy damage of the tested material because the process of control applies the immersion when the contact with water may cause the damage of the material, or compressed air.

Gholizadeh S. reviewed non-destructive testing (NDT) methods of composite materials which use contact and non-contact control technologies [10]. These methods have been successfully used for a long period of time due to the fact that composite materials are mostly used in critical-safety applications for example in aircraft primary constructions. Assuming that factors such as efficiency and safety should be used in analyzing the best method to be used, the method chosen should minimize the costs incurred in the operation. Therefore, it is important to bring to the light inexpensive but highly efficient method to test composite and non-composite materials by the non-contact ultrasound method [11]. This engineering innovation is based on an equipment that doesn't need special qualification of the operator, as compared to other non-destructive testing methods. In particularly, an advantage of this method is the possibility to determine the damage of the material structure that may occur under the load, the effect of the damage on the load-bearing capacity of structures, as well as the analysis of the behavior of composites in difficult working conditions (temperature and humidity variations, vibrations, the effect of chemical agents, mechanical impact, etc.).

Nowadays are described various techniques of the non-contact ultrasound control method. For example, Petroni P. et al. (2006) proposes to place the transmitter transducer in transmission configuration, but the receiver to be placed obliquely on the same side of the emitter, in order to let it acquire the scattered waves generated by the defect [12]. Authors investigated Delta configuration using non-contact probes in an attempt to evaluate potentials and performance of the studied techniques, and defect identification capabilities. The research team concluded that an important issue for defect detection capability is the determination of the optimal probes position.

Experimental part

Lamb waves represent elastic waves which were first described in 1917 by the English mathematician Horace Lamb. They propagate in solid plates in two wave modes, and their velocities depend on the relationship between wave length and plate thickness. The symmetrical mode S_0 of the Lamb waves is easier to be transmitted and received as compared to asymmetric mode A_0 through the non-contact technique [13]. The mechanism of detecting the defect in solid plates consists of "scattering" the Lamb waves in the defect area. This process forms an increased attenuation of the ultrasound with respect to a defect-free plate, similarly, the phase speed reaches a lower level in the defect plate than in the defect-free one [14].

The defect index represents the change of amplitude on the axis of movement of the transducers. However, for the excitation of Lamb waves in a plate, it is necessary to know the oblique angle of the incidence [15]. The relationship between the excitation angle and the phase velocity of Lamb waves can be written according to Snell's law by the Eq.(1) [16]:

$$\phi_1 = \left(\frac{c_{air}}{c_f} sin\,\phi_2\right) = arcsin\left(\frac{c_{air}}{c_f}\right); \tag{1}$$

Where: ϕ_1=ϕ_2- is the excitation angle of the *n* Lamb waves; C_f - is the phase velocity of the *n* Lamb wave; C_{air} – is the propagation speed of ultrasound in the air.

According to Snell's law, if excitation angle ϕ_1 is known, the phase velocity of Lamb waves mode A_0 can be found out. For this reason, was designed and manufactured a device to help find experimentally the excitation angle of Lamb mod A_0 waves in the plates (Figure 1):

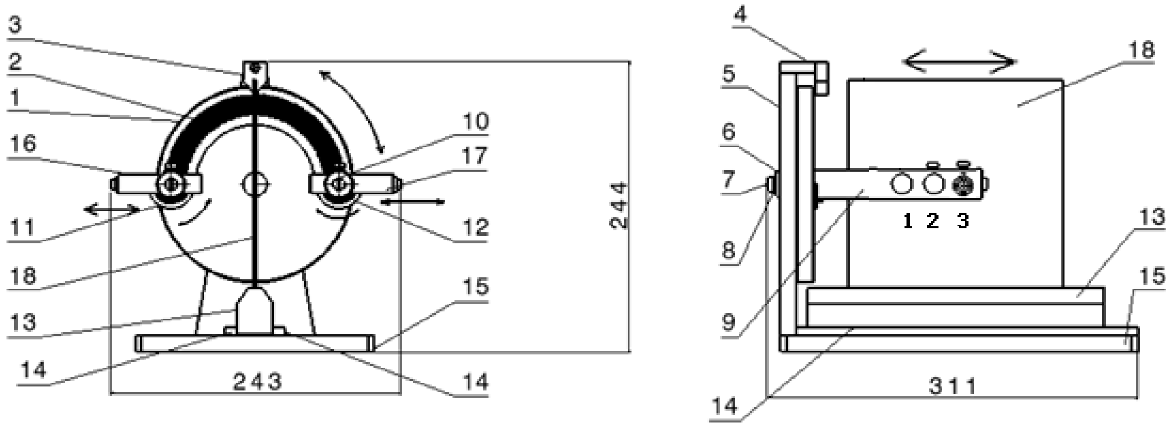

Figure 1. Schematic presentation of the device for finding the optimal excitation angle of Lamb waves asymmetrically mode A_0 in plates.
1 - wheel; 2- the main rapporteur; 3 - needle; 4 - needle support; 5 - wheel support; 6 - bush; 7 - axle; 8 - axle snap ring; 9 - support for emission transducers; 10 - support for reception transdu-cers; 11 - secondary rapporteur 1; 12- secondary rapporteur 2; 13 - plate holder; 14 - guides; 15 - base plate; 16 - non-contact ultrasonic emission transducer; 17 - non-contact ultrasonic reception transducer; 18 - plate to testing.

To find the optimal excitation angle of the Lamb waves mode A_0 in the plate, proceed as follows:

a) insert a sample (Figure 1, p. 18) with maximum dimensions of 180 mm x 200 mm (plates with relatively small thicknesses compatible with non-contact control such as aluminum, reinforced composite plates, or sandwich plates in the plate holder (Figure 1, p. 13).
b) Non-contact ultrasonic transducers (Figure 1, p. 16 - 17) are fixed in transducer supports (Figure 1, p. 9-10) at the beginning at a maximum distance from the plate, and it's connected by wires (Figure 2, p. 19) to the ultrasonic equipment SITAU 32:128:2 LF (Figure 2, p. 20) which in turn is connected to the computer (Figure 2, p. 22) by wires (Figure 2, p. 21) for viewing, recording and processing signals with the maximum amplitudes obtained (Figure 2).
c) By rotating the wheel (Figure 2, p.1) together with the non-contact transducers (Figure 2, p. 16 - 17) with minimum possible rotation step $0{,}5^0$ stops when the maximum amplitude is observed on the monitor. Record the angle obtained (the value on the main rapporteur (Figure 1, p.2) opposite the indicator (Figure 1, p. 3) is φ_i.

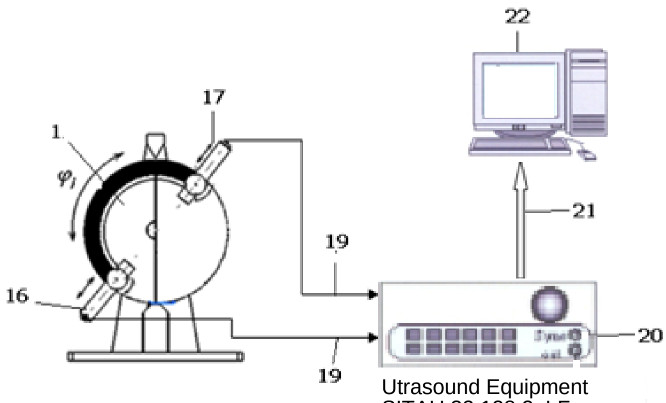

Figure 2. Ultra-acoustic system for finding the optimal excitation angle of Lamb A_0 mode waves in the plate.

d) The next step consists of rotating the transducer supports (Figure 3, p. 9 - 10) around their axis to find the φ_1 and φ_2 angles, also the transducers approach or their removal from the plate to obtain the maximum amplitude, the values *A* and *B* (Figure 3).
e) The obtained values (A, B, C, ϕ_i, ϕ_1, and ϕ_2) will be used later for the positioning and fixing of the non-contact ultrasonic transducers (Figure 3, p. 16 - 17) in the manual non-contact investigation device with ultrasound of the plates (Figure 10) with larger dimensions but with the same structure and thickness, with and without defects.

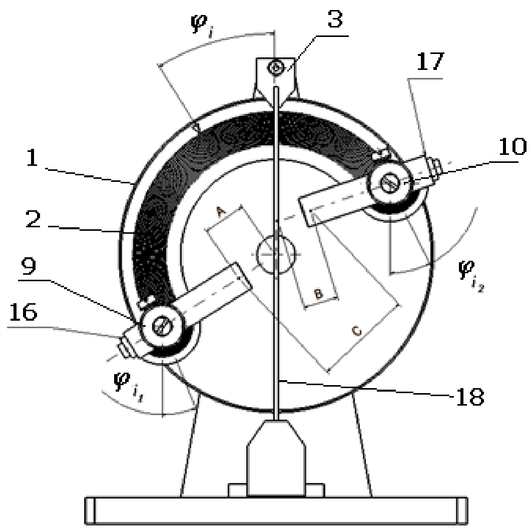

Figure 3. Device for experimental determination of the values *A, B, C, φ_i, φ_1* and *φ_2*.

In the first experiment, was used an aluminum plate with dimensions of 180 x 200 x 2.5 (mm) and a pair of non-contact ultrasonic transducers with the optimal frequency of 450 kHz positioned in the transmission respectively reception mode (Figure 2). The transmitter was energized with rectangular pulses and a current voltage of 750 V using the ultrasonic system SITAU 32: 128: 2 LF. The received signal was amplified to 34 dB using the built-in noise reduction amplifier in the SITAU 32: 128: 2 LF ultrasonic system. To obtain a better signal/noise ratio (SNR), 54 signals were emitted at each measurement step. The experimentally obtained signals were stored in the PC for further processing in MATLAB and the formation of ultrasound images.

An aluminum plate (Figure 1, p. 18) was inserted into the plate holder (Figure 1, p. 13) between the transducers (Figure 2, p. 16 - 17), the wheel (Figure 1, p. 1) was rotated in an angular field from $+30^0$ till-30^0, step by step with 0.5^0.

Experimentally, a type B image was obtained, which shows a dependence between the received signal and the rotation angle φ_i of the non-contact transducers for 450 kHz (Figure 4).

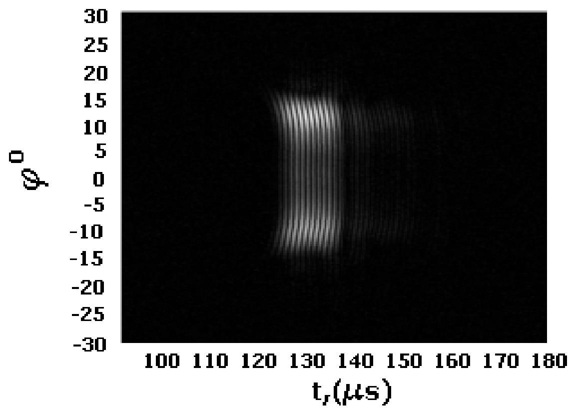

Figure 4. Type B image of A_0 asymmetric mode Lamb waves obtained by rotating the wheel from -30^0 till $+30^0$ using non-contact transducers at f=450 kHz (aluminum plate 2.5 mm thickness).

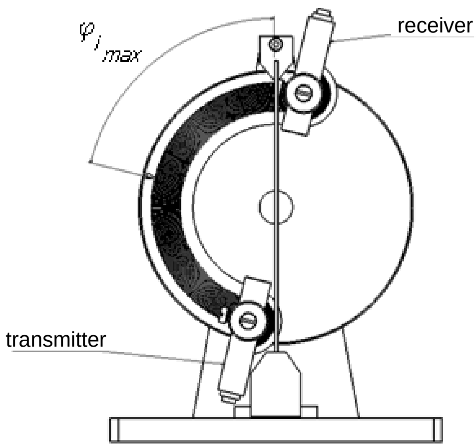

Figure 5. Obtaining the shortest time of wave propagation in the plate by rotating the wheel at the $\varphi_{i\ max}$ angle.

It was observed that the shortest time of the propagation of the ultrasonic waves corresponds to the maximum angle $\varphi_{i\ max}$ (Figure 5):

This is explained by the fact that the speed of ultrasound propagation in the aluminum plate is much higher than the speed of ultrasound in the air [17].

The optimal angle of excitation of the Lamb waves mode A_0 in the aluminum plate with 2.5 mm thickness obtained experimentally at the frequency of 450 kHz corresponds to the maximum amplitudes (Figure 6).

A type B image was also obtained to shows a dependence between the received signal and the rotation angle φ_i of the non-contact transducers for 250 kHz (Figure 7).

The phase velocity of the Lamb waves asymmetric mode A_0 can be measured with an uncertainty of 2.5% in the case of non-contact investigation techniques.

From the diagram, figure 8, it can be seen that in the aluminum plate there are only Lamb waves asymmetric mode A_0, the optimal excitation angle respectively reception is $\pm 10{,}7^0$.

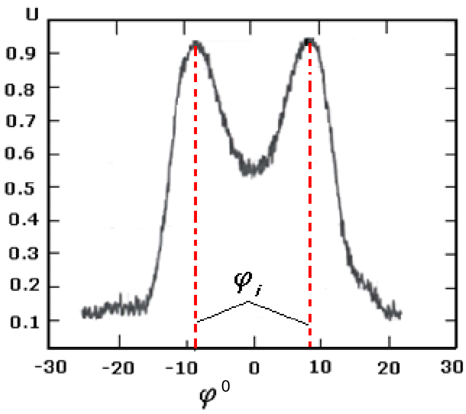

Figure 6. The maximum amplitudes obtained by rotating the main wheel from $+30^0$ till -30^0 at the frequency of 450 kHz, $\varphi_i = \pm 9^0$ are the optimal angles for excitation and reception.

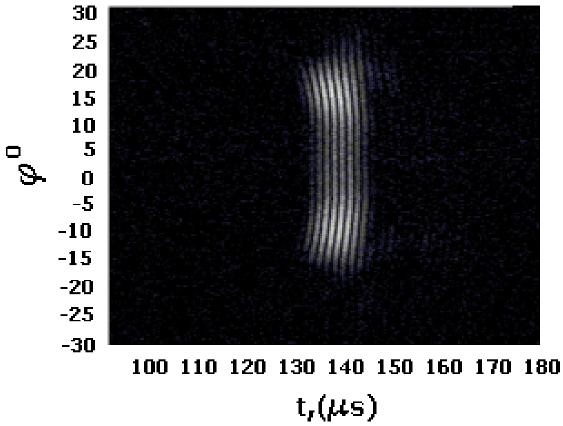

Figure 7. Type B image of the signals received by rotating the main wheel from -30^0 till $+30^0$ by using non-contact transmission and reception transducers with *f = 250 kHz.*

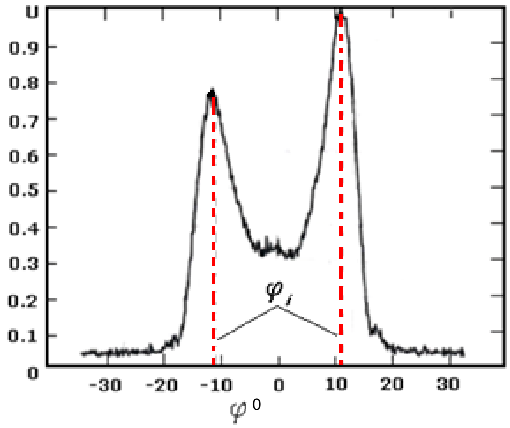

Figure 8. Maximum amplitudes of Lamb waves mode A_0 obtained at *f = 250 kHz.* $\varphi_{1,2} = \pm 10.7^0$ are the optimal oblique angles of incidence for excitation and reception.

Given the optimal angle, according to Snell's law showed in Eq.(1), can be calculated the phase velocity of propagation Lamb waves mod A_0 through the aluminum plate at the frequency of 250 kHz, the result is 1850 m/s. The speed of propagation of ultrasound in the air during the measurements was 345.4 m/s at 22.3^0 C and relative air humidity of 35%. In the Table 1 is shown the data of the experimental measurements and the calculated data:

Table 1

	Incidence angle (ϕ_i)	Experimental measurement		Calculated	
f, kHz	Degree	c mode S_0, m/s	c, mode A_0, m/s	c, mode S_0, m/s	c, mode A_0, m/s
250 kHz	$10{,}7^0$	5470	1850	5481	1893
450 kHz	9^0	5190	2250	5222	2253

Dispersion curves of the phase velocities and of the group velocities of the Lamb waves in the 2.5 mm aluminum plate thickness are presented in the Figure 9. They were calculated according to the analytical solution, considering that the propagation speed of the longitudinal ultrasonic waves in aluminum is 6320 m/s and of the transverse ones 3130 m/s [18].

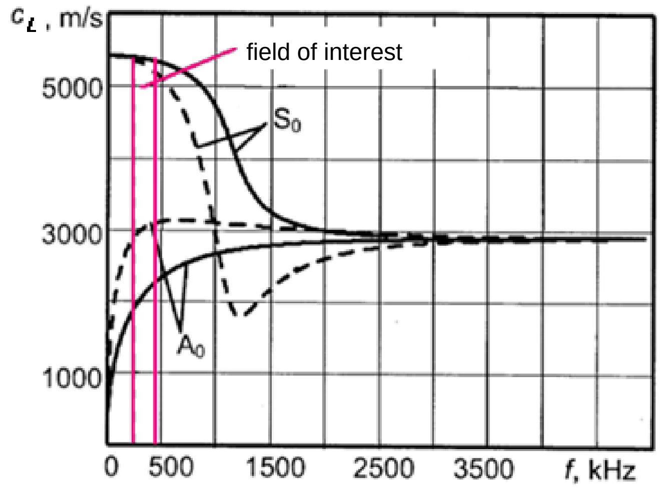

Figure 9. Dispersion curves of the measured velocities phase (continuous lines) and of the group (dashed lines) propagation velocities of Lamb mode A_0 and S_0 waves.

It was observed that the asymmetric group speeds increase and the symmetric ones decrease with the frequency. The influence of frequency can also be mentioned on the angle of generation of Lamb waves in plates. After recording the obtained constants (A, B, C, ϕ_i, ϕ_1, and ϕ_2) the transducers can be removed and fixed in the manual device (Figure 10) with the same values for the investigation of 2.5 mm thick aluminum plates.

The same procedure will be done for each material, for example: must to find the optimal excitation angle of the Lamb A_0 waves for the carbon fiber reinforced plate, record the values *A, B, C,* φ_i, φ_1, and φ_2, remove the transducers and fix them manually with the same values for the investigation of carbon fiber reinforced plates with or without defects, with the same structural composition and thickness.

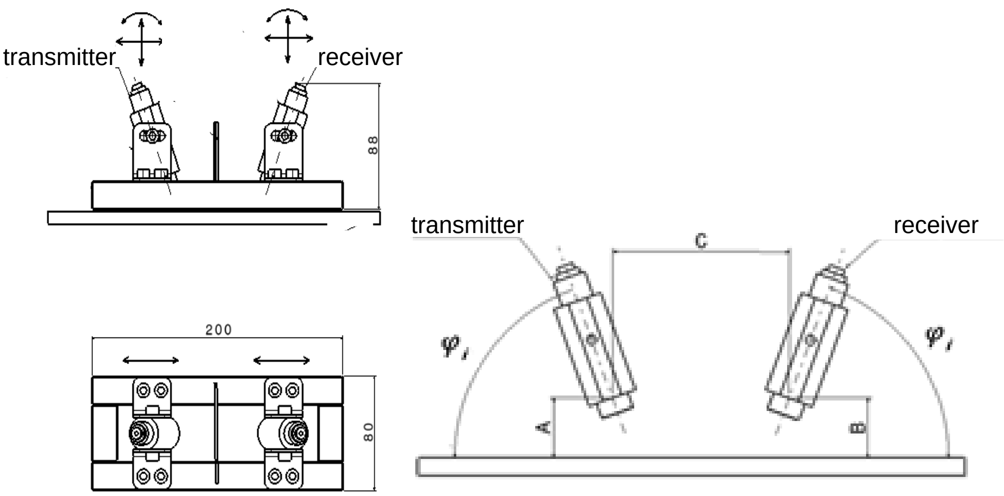

Figure 10. Manual device of investigation (left), fixing non-contact acoustic transducers (right).

In the next experiment, the transmitting transducer was inserted into the hole no.2 and the receiving one into the hole no.3, so the distance between the axes of the non-contact transducers reached 25 mm. The one-way carbon fiber reinforced plate 1.1 mm thick was inserted into the composite plate support (Figure 11):

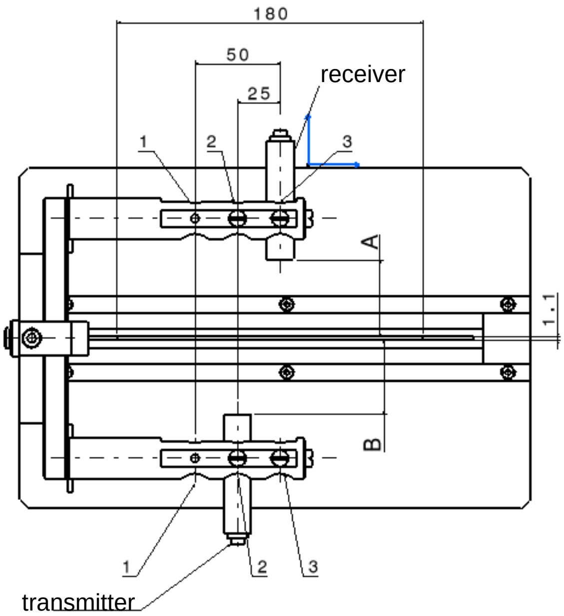

Figure 11. Non-coaxial placement of the non-contact ultrasonic transducers.

The transmitter was energized with rectangular pulses at a current voltage of 650 V using the ultrasonic system SITAU 32: 128: 2 LF at the frequency of 250 kHz and the receiver signal was amplified by 45 dB. The wheel (Figure 1, p. 1) was rotated step by step with 0.5^0. The maximal amplitudes were obtained in an angular field from $+25^0$ till -25^0 with the adjustment of the values *A, B, C*, φ_i, φ_1, and φ_2. As a result, was obtained the angle of 15.5^0, which is optimal angle of excitation of Lamb waves asymmetric mode A_0 (Figure 12):

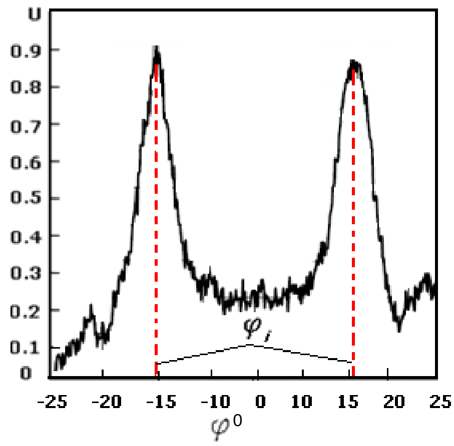

Figure 12. The optimal incidence angles for generating Lamb waves mode A_0, the distance between the axes of the transducers 25mm, *f = 250 kHz.*

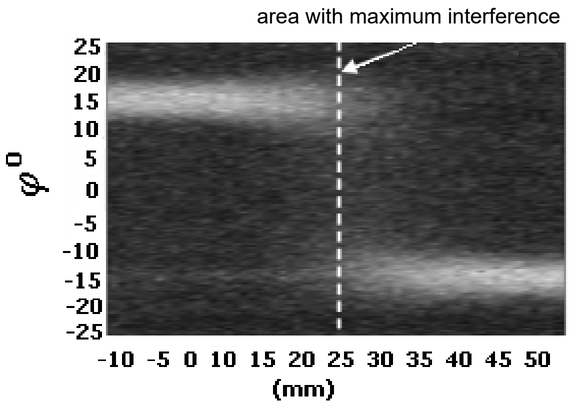

Figure13. Type C image of received Lamb mode A_0 waves, f = 250 kHz.

Respectively, the phase velocity of the Lamb waves asymmetric mode is 1290 m/s. Subsequently, with the obtained signals was formed a type C image of the received waves (Figure 13) which shows the area with the maximal interference of Lamb waves when the distance between the axes of the transducers is 25 mm and respectively the angles of incidence ϕ_i is equal to $15,5^0$.

Another objective of the experiment was an attempt to move the axis of the transmitter transducer by 50 mm from the receiver axis, but no consistent results were obtained.

Conclusions

The paper addresses the issue of choosing the angles of incidence for the transmission and reception of Lamb ultrasonic waves during the control of plate-type parts by the non-contact ultrasound method. The experiment resulted with the design and manufacture of two devices: the first one was aimed to set the values of A, B, C, ϕi, ϕ1, and ϕ2, depending on the maximum amplitudes of the obtained signal; the second device was used to position the transducers with the obtained values and to control the plates of the same material and thickness with or without defects.

An observation of the experiment was that the asymmetric group speed increases with the frequency and the symmetric ones decreases with the frequency. The frequency of the non-contact ultrasonic transmitting transductor directly influences the angle of the incidence of Lamb waves in the plates. A better signal/noise ratio was obtained by moving the axis of the transmitting transducer with f equal to 250 kHz in relation to the axis of the receiver by 25 mm. Also, velocity phase of the Lamb waves decreased from 1353 m/s to 1290 m/s. Consecutively, the angle of incidence $\varphi_{1,2}$ of the Lamb waves generation increased from 14.7^0 to 15.5^0.

Concerning materials with complex geometry, such as wings and propellers of the aircraft, the non-coaxiality of the non-contact transducers is not suitable for the control, because it may increase the rate of errors in data interpretation regarding the defect position and size.

Acknowledgments: I would like to express my special thanks of gratitude to Prof. Amza Gheorghe and his team from the University POLITEHNICA of Bucharest (Romania) for his help in the experimental and theoretical part of the research work and Acad. Ion Bostan from Technical University of Moldova who inspired me to publish these results.

References

1. Victor Giurgiutiu. „Boeing 787 Dreamliner" in „Structural Health Monitoring of Aerospace Composites" Published 2015.
2. Van Den Abeelen. „Spaceplane HERMES ,Europe's Dream of Independent Manned Spaceflight" Published 2017. pp. 417 - 433
3. F.C. Campbell. „ Structural Composite Materials" November 2010, ASM International, Materials Park, Ohio 44073-0002, ISBN-13:978-1-61503-037-8; ISBN-10:0-61503-037-9; SAN 204-7586
4. Maria Mrazova „ Advanced composite materials of the future in aerospace industry" September 2013, INCAS Bulletin 5(3):139 - 150
5. Robert E Green. Non-contact ultrasonic techniques. Ultrasonics 42 (1 - 9), May 2004: pp. 9 - 16
6. Mariusz Kaczmarek, Bogdan Piwakowski, Radosław Drelich. „Noncontact Ultrasonic Nondestructive Techniques" State of the Art and Their Use in Civil Engineering. Journal of Infrastrucure Systems / Volume 23 Issue 1- March 2017
7. Gheorghe I. Gheorghe, Hacman Mihai, Florin Andrei, Alexandru Buga. „ Intelligent machine for dimensional control and marking "Power transfer unit" for the auto subassemblies in large-scale seriesproduction" IEEE International Conference on Mechatronics 13-15 April, 2011 Istanbul, Turkey, Pag: 933 – 936, Print ISBN: 978-1-61284-982-9.
8. Gheorghe I. Gheorghe, Hacman MihaI, Florin Andrei, Alexandru Buga. „Mechatronic intelligent unit for tightness checking reverse module TL8" – machined *IEEE International Conference* on Mechatronics 13-15 April, 2011 Istanbul, Turkey, pag. 930 – 932,Print ISBN: 978-1-61284-982-9.
9. Gheorghe I. Gheorghe, Vrabioiu Ion, Andrei Florin, Nineacă Dan, Alexandru Buga. „Intelligent mechatronic unit for tightness checking case timing H5 (machined)" E-newsletter „MECATRON" Octombrie 2012, pag. 7 - 8
10. Gholizadeh S. A review of non-destructive testing methods of composite materials / Procedia Structural Integrity 1 (2016) 050 – 057

11. B. Boro Djordjevic „Advancements in Ultrasonic Imaging for Materials Testing" Acoustical Imaging - book series ACIM, volume 26, pp. 289 - 296.
12. Petroni P, Revel Gm. „Non Contact Ultrasonic Techniques for Composite Material Diagnostics in Aeronautics Applications" ECNDT Conference at Berlin in 2006
13. Horace Lamb. „On waves in an elastic plate", F.R.S.(1916, July 10)
14. Soleimanpour R. and NG CT.„Scatttering of the fundamental anti-symmetric Lamb wave at through thickness notches in isotropic plates"Journal of Civil Structural Health Monitoring 6(3) (July 2016): pp. 447 - 459
15. Sandeep Sharma, Abhijit Mukherjee. „Damage detection in submerged plates using ultrasonic guided waves" Indian Academy of Sciences, Sadhana Vol. 39, Part 5, October 2014, pp. 1009 – 1034
16. Kwan A., Dudley J., Lantz E. (2002) „ Who really discovered Snell's law?" Physics World.15(4):64
17. Tomás Gómez Álvarez-Arenas, Jorge Camacho. „Air-coupled and resonant pulse-echo ultrasonic technique" published at 14 may 2019 in New methods and applications of nondestructive testing in close ranging)
18. Dixon P., Petcher Y., Fan D. Maisey and P. Nickolds. „Ultrasonic metal sheet thickness measurement without prior wave speed calibration" published 17 october 2013 at journal of physics: applied physics, volume 46, number 44.