

1 **Experimental and numerical identification of corrosion degradation of ageing structural** 2 **components**

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8 **Abstract**

9 The study presents experimental and numerical identification of corrosion degradation of thin-
10 walled structural components employing guided wave propagation. The steel structural
11 components are subjected to through-thickness varying corrosion degradation levels. The
12 developed approach using the non-destructive guided wave-propagation quantifies the
13 equivalent average corrosion degradation level exploring a limited number of transducers. A
14 group velocity dispersion curve reconstruction has been used to determine the corrosion-
15 induced plate thickness reduction. Two case studies are used to examine experimentally the
16 newly developed approach. In the first one, the dispersion curve and the assessment of the
17 corrosion thickness reduction have been made using wave signals of various excitation
18 frequencies. In the second one, the analysis has been conducted only for two wave propagation
19 signals and one excitation frequency which allowed for reconstructing the dispersion curve in
20 a limited frequency range. In both case studies, a good agreement between the natural and
21 estimated corrosion degradation levels was observed. The present study develops a signal
22 processing methodology, which can be used in the SHM systems, where several aspects still
23 need to be further investigated before it can be applied in large size and complex geometry of
24 ship hull structures.

25 **Keywords:**

26 corrosion degradation; steel plates; ship structures; NDT; ultrasonic waves

27 **1 Introduction**

28 Ships and offshore structures are operating in a highly corrosive environment. The
29 excessive corrosion degradation may lead to catastrophic consequences, e.g., exceedance of the

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30 ultimate strength of ship structural components (Woloszyk et al., 2018) and entire ship hull
31 (Parunov et al., 2007). According to Zayed et al. (Zayed et al., 2018), even up to 90% of ship
32 hull damages are primarily or indirectly caused by corrosion. An example of tanker ship loss,
33 mainly driven by excessive corrosion degradation, breaking the ship's hull in two parts, is the
34 tanker Prestige in 2002 (Flashback history: Tanker Prestige sinking (Video), 2015).

35 There are regular surveys of the entire ship to avoid severe degradation, where the
36 thickness of structural components is measured using an ultrasonic thickness gauge. This
37 method has various advantages, i.e., the equipment is portable, and the usage is user-friendly.
38 However, it provides information about thickness in one point of any particular measurement.
39 Thus, numerous thickness measurements must be done to correctly map the distribution of
40 thickness corrosion diminutions within larger structures like ship hulls.

41 Cegla and Gajdacs (Cegla and Gajdacs, 2016) found that irregularities in corroded
42 surfaces disturb the ultrasonic measurements and usually overestimate the corroded plate
43 thickness value. Similar observations have been found in (Woloszyk et al., 2021). Zayed et al.
44 (Zayed et al., 2008) analysed the factors that may disturb the ultrasonic measurements, e.g.
45 lighting, cleanliness and accessibility to the inspected area. Additionally, there is always a
46 probability that some deteriorated structural components are omitted during the inspections.
47 Such a possibility may be seen in a more difficult area for inspection as double bottom or closed
48 spaces.

49 To reflect some problems faced with using the non-destructive measuring techniques,
50 some new approaches were developed, especially based on guided waves, which were proved
51 to be very useful in diagnostics of both localized damages (Cao et al., 2021; Wandowski et al.,
52 2011; Zima, 2021), as well as surface damages (Ding et al., 2021; Hu et al., 2022; Zima and
53 Rucka, 2017). The guided wave propagation seems to define the corrosion degradation level
54 around the structural components effectively. The most advantageous feature of the guided
55 wave propagation approach is mapping a larger area of the thickness of structural components.
56 Moreover, high-frequency wave-based methods are generally insensitive to applied loads and
57 low-stress levels (the differences in wave velocities are negligible), which significantly
58 facilitates the analysis and results interpretation (Li et al., 2021).

59 Ervin and Reis (Ervin and Reis, 2008) tested the guided waves' low and high-frequency
60 ranges to monitor the reinforced bar's corrosion degradation in mortar specimens. Ervin et al.
61 (Ervin et al., 2009) used longitudinal ultrasonic waves of high frequencies to monitor the
62 reinforced mortar specimens undergoing accelerated uniform and localised corrosion.

63 Two ultrasonic techniques of pulse transmission and pulse-echo were used to monitor the
64 healthy and damaged bar by Sharma and Mukherje (Sharma and Mukherjee, 2010). Fractal
65 analysis of guided ultrasonic waves for evaluating the corrosion degradation level in post-
66 tensioned systems was proposed by Moustafa et al. (Moustafa et al., 2014). Farhidzadeh and
67 Salamone (Farhidzadeh and Salamone, 2015) used dispersion curves, continuous wavelet
68 transform, and wave velocity measurement to quantify the corrosion damage of multiwire
69 prestressing steel strands.

70 In all reported cases, the corrosion degradation was accelerated by applying the direct
71 current. The level of corrosion degradation (mass loss) was linearly dependent on corrosion
72 current and time elapsed. The corrosion degradation assessment was based on the analysis of
73 the dispersion curves. Because the shape of dispersion curves mainly depends on the geometric
74 parameters, monitoring the trace changes efficiently assessed the corrosion degradation level.

75 Recently the methods of dispersion curve reconstruction have been extensively studied.
76 However, the dispersion curve reconstruction demands multiple measurements along the
77 relatively short propagation path, which would be inefficient in a large-scale structure like
78 offshore platforms or ships (Draudviliene et al., 2021). Finally, there are almost no studies
79 regarding guided wave propagation to identify the corrosion degradation of thin-walled
80 structures subjected to environmental corrosion. Most of the studies were related to localised
81 pitting corrosion (Ciampa et al., 2015; Ding et al., 2021; Howard and Cegla, 2017; Hua et al.,
82 2020; Tian et al., 2021). The corrosion degradation observed in ship structures is mainly general
83 (Panayotova and Garbatov, 2010), although pitting one is quite common too. General corrosion
84 is observed, e.g., in cargo holds as well as in ballast tanks.

85 Recently, the study aimed at a corrosion assessment using the guided ultrasonic waves
86 (Zima et al., 2022), contained a detailed description of a methodology based on the phase
87 velocity and convex optimization. The study performed here is the next step aimed at procedure
88 simplification and reducing the extent of the sensors network, as well as the collected data in
89 the future SHM systems. Previously employed phase velocity was determined using spectral
90 decomposition and the zero-cross method. Because of the dispersive nature of guided waves
91 and spreading the wave packet, the unambiguous identification of corresponding roots may be
92 associated with impediments to interpretation. Moreover, it was proved that usually the phase
93 velocity is overestimated which leads to underestimation of corrosion degradation level [20].
94 Therefore, in the following study, the approach based on dispersion curve reconstruction has
95 been modified and we have used the Hilbert transform and group velocity curve to assess the
96 degradation level of thin-walled ship structures. Such modifications allow for simplification of

97 the signal processing procedure. The newly developed approach's main advantage is that only
98 two adjacent wave propagation signals are needed in the identification process. The limited
99 number of essential signals processed within the algorithm is extremely important from the
100 point of view of the further development of the diagnostics systems and data communication.
101 The smaller number of signals requires fewer measurements which in turn means a smaller size
102 of memory and the whole size of the potential devices. Additionally, the smaller size of the
103 device and a limited number of excitations and registrations entail longer battery life and lower
104 costs of equipment maintenance. Although the presented algorithm is only the first step in the
105 development of the diagnostics methods for ship structural monitoring and its requirement
106 improvements which are faithfully discussed in the paper, the small amount of necessary data
107 is one of its most significant advantages.

108 The corrosion degradation level of a significant area may be assessed, which makes the
109 newly developed approach far more effective than the standard one of the ultrasonic thickness
110 measurement or wave tomography. The analysed corroded thin-walled structural components
111 were initially corroded employing an originally designed corrosion deterioration set-up. The
112 corrosion degradation process was in line with in-situ environmental degradation. The designed
113 corrosion deterioration set-up has a significant advantage over the efficient DC-induced
114 corrosion degradation and leads to more realistic surface characteristics (Xiao et al., 2020; Yuan
115 et al., 2007), but is still very different from the real one.

116 Based on the obtained reconstructed dispersion curves the corrosion degradation level has
117 been assessed. To analyse the effectiveness and accuracy of state assessment of the specimen,
118 the analysis stage has been divided into two stages. Within the first stage, five different
119 frequencies were used in the study and the curves have been reconstructed in the wide frequency
120 range. At the second stage, the curve was traced only for a narrow frequency range
121 reconstructed after one excitation. In both cases, the progress of corrosion degradation affected
122 the shape of the curves. The results collected within both stages were compared with the actual
123 one determined by mass calculation. The agreement between the results suggests the potential
124 of the novel method in corrosion degradation monitoring. The article discusses both advantages
125 and disadvantages of the proposed method.

126 2 Guided waves propagation in thin-walled structures

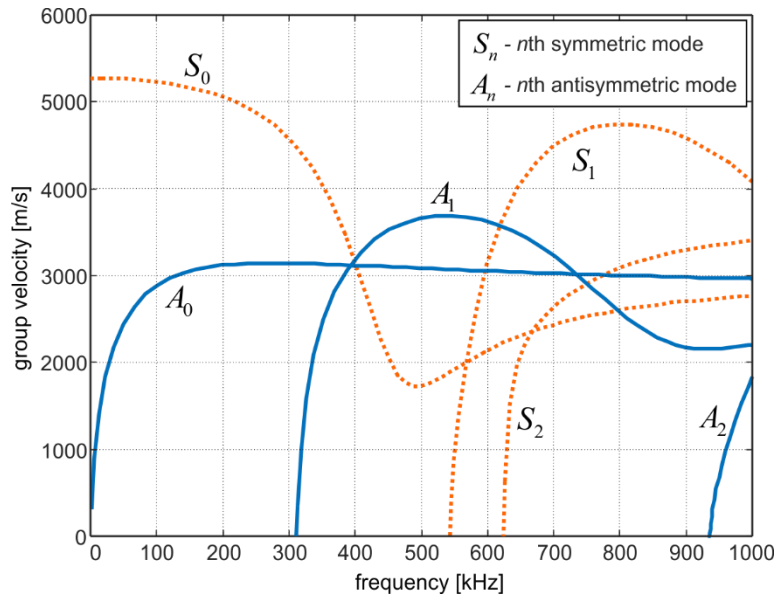
127 2.1 Theoretical background

128 The guided waves in plates are generated due to the interaction of compressive and shear
129 waves propagating in elastic, homogeneous, isotropic medium bounded with two equidistant
130 surfaces. Horace Lamb foresaw their existence (Lamb, 1917) and derived dispersion equations
131 relating to the propagation velocity and the number of possible wave modes with an excitation
132 frequency. In general, the Lamb waves can exist as symmetric and antisymmetric. They are
133 high dispersive, and their propagation velocity depends on the frequency and plate thickness
134 product. Two equations describe the dispersive characteristics of both types:

$$135 \frac{\tan(qd)}{\tan(pd)} = -\frac{(k^2 - q^2)^2}{4k^2 pq}, \quad (1a)$$

$$136 \frac{\tan(qd)}{\tan(pd)} = -\frac{4k^2 pq}{(k^2 - q^2)^2} \quad (1b)$$

137 where d is the plate thickness and the parameters p and q depend on wavenumber k , angular
138 frequency ω , longitudinal wave velocity (c_L) or shear wave velocity (c_T) in the infinite
139 medium. The velocities of guided and bulk waves depend also on the material parameters of
140 the considered medium. Eqn 1a is associated with symmetric particle motion about the
141 midplane, while Eqn 1b describes the antisymmetric particle motion caused by wave
142 propagation. The number of possible solutions fulfilling the Eqn (1) is infinite, and in general,
143 the roots may be complex. However, the real roots are associated with propagating waves, while
144 imaginary roots corresponding to evanescent waves will not be considered in further analysis.
145 The solution of the dispersion equation is presented in the form of dispersion curves. At least
146 one symmetric mode (S) resembling axial waves and one antisymmetric mode (A) resembling
147 flexural wave exists for each frequency. The number of possible curves associated with any
148 particular wave mode increases with the increase of the considered frequency range. The
149 exemplary dispersion curves traced for a steel plate are presented in Figure 1.



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Figure 1 Dispersion curves for a steel plate with a thickness of 5 mm, elastic modulus $E = 198$ GPa, $\nu = 0.3$ and density $7,850$ kg/m³

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It has to be pointed out that the Lamb theory is valid only for plates with constant thickness, and their material fulfils the conditions of elasticity, homogeneity, and isotropy. Meanwhile, the corroded specimens are usually covered with corrosion products varying in mechanical properties from the undamaged core. In general, the additional layers require different wave theories, but in the following study, the corrosion products were removed before the investigation to assess the damage degradation level. This research will verify the correctness of the assumption about the constant thickness.

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2.2 Signal processing procedure

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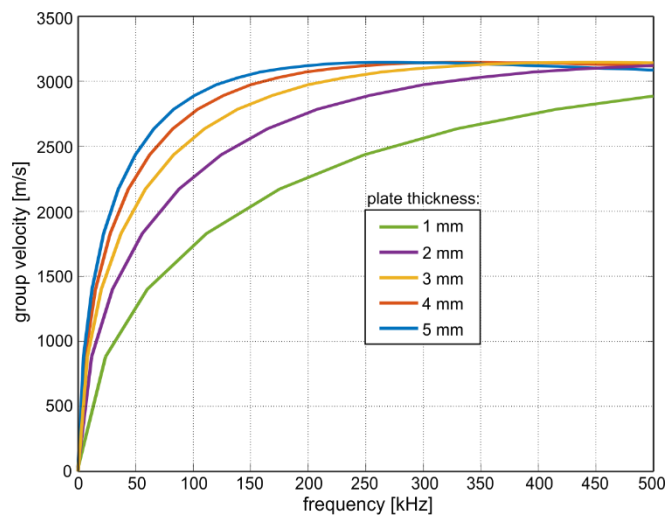
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As mentioned, the shape of dispersion curves depends on the material and geometric parameters of the considered plate. The proposed approach for a corrosion level assessment assumes that corrosion degradation influences the thickness of the plate. At the same time, the elastic modulus, density, and Poisson's ratio are considered to remain unaffected. In consequence, the shape of the dispersion curve depends on the corrosion deterioration level. In general, the assumption about the constant material parameters is not valid for cases of corroded structures and will be verified in this study. However, the plate thickness is the most influential factor, and its variation affects the wave velocity the most. Figure 2 presents the dispersion curve associated with the first antisymmetric Lamb mode in the frequency range (0-500 kHz) for steel plates with varying thicknesses. For some frequencies, the degree in the group propagation velocities is significant (i.e., 100 kHz). In contrast, for some frequencies, the curves

172 coincide with each other, which indicates that the corrosion degradation (plate thickness
173 reduction) does not impact the wave propagation (i.e., 400-500 kHz).

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176 Figure 2 Dispersion curve associated with the first antisymmetric Lamb mode for plates with a varying thickness

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178 Moreover, the corrosion degradation impact depends on the initial parameters of the
179 uncorroded plate. One-millimetre thickness reduction in a plate with an initial thickness of 5
180 mm results in an insignificant change in the dispersion curve shape. In contrast, in the case of
181 thinner plates, the difference is noticeable. There is no explicitly given relationship between the
182 frequency, propagation velocity, and thickness reduction. However, for every thickness,
183 frequencies of corrosion damage can be identified. The newly developed approach here aims to
184 reconstruct the dispersion curve representing group velocity, enabling a better estimation of the
185 average plate thickness during corrosion degradation.

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187 The corrosion degradation level identification is based on measuring at least two signals
188 by the transducers attached at two distinct positions. The distance between the actuator and
189 sensors should be established by taking into account the dispersive nature of guided waves,
190 signal attenuation, the energy of the input wave, and the size of the area, which is monitored.
191 The shorter distance results in a greater signal-to-noise ratio (SNR), which facilitates the
192 interpretation of the results. The longer distance allows for assessing a greater area of the tested
193 structure.

194

195 The algorithm presented here aimed at the reconstruction of dispersion curves using
196 adjacent signals has been also analysed and utilized by other researchers (Draudviliene et al.,
197 2021; Zima et al., 2022). The main development is its modification for group velocity extraction
and employment in the corrosion degradation assessment. For clarity, a brief description of the
following steps is presented here.

198 In the first step of the developed approach, the guided Lamb waves are excited by an
 199 actuator triggering a narrowband burst. In this study, the five-cycle sinusoid modulated by the
 200 Hann window is used (Lyons, 2011):

$$201 \quad p(t) = \begin{cases} p_0 \sin(2\pi ft) \cdot w(t) & t \in [0, T_w] \\ 0 & t \geq T_w \end{cases}, \quad (2)$$

202 where f is the excitation frequency, p_0 denotes the excitation amplitude, and T_w is the modulating
 203 window length. The modulation window is described by a function:

$$204 \quad w(t) = 0.5 \left(1 - \cos \left(\frac{2\pi ft}{n_w} \right) \right), \quad t \in [0, T_w], \quad (3)$$

205 Next, the incident waves captured by sensors are identified and extracted from the
 206 adjacent signals (Figure 3, stage II). The reflections from the edges or other obstacles registered
 207 further in the signal are not considered, significantly simplifying the analysis, which is one of
 208 the most important advantages of this approach, especially in the context of the further research
 209 dedicated to diagnostics of large and complex structures. The trigonometric representations of
 210 the incident waves are calculated using the Fourier integral and the frequency response
 211 amplitude (Figure 3, stage III). The spectrum is normalised as the maximum value equals 1.0
 212 in each case (Figure 3, stage IV). Based on the frequency ranges of the obtained spectra, the
 213 frequency limits f_L and f_H are established. In general, the spectrum vanishes above the upper-
 214 frequency limit f_H and below the lower frequency limit f_L (Figure 3, stage V). Regardless of
 215 the spectra' differences for signals registered during the same measurement, the frequency limits
 216 are the same. Next, the frequency spectra $S(f)$ are filtered by using n bandpass filters defined
 217 as a Gaussian magnitude function:

$$218 \quad U_k(f) = S(f) B_k(f) = S(f) e^{4 \ln(0.5) \left(\frac{f - f_L - (k-1) \Delta f}{\Delta B} \right)^2}, \quad (4)$$

219 and $k=1, 2, \dots, n$. According to recommendations formulated by He (Ping He, 1998), the number
 220 of filters n depends on the bandwidth parameter ΔB , which defines the frequency range limited
 221 by the single filter:

$$222 \quad n > 1 + \frac{f_H - f_L}{\Delta B}, \quad (5)$$

223 Here, the bandwidth parameter ΔB was determined based on the normalised Fourier
 224 frequency spectrum. Its value was established based on the spectrum width for the normalised
 225 amplitude corresponding to the -3dB value. In the next stage, the signal is synthesised from the
 226 basic trigonometric functions by using the inverse Fourier transform (Figure 3, stage VI).

227 Finally, the time of flight was determined by the envelope method. The envelope of the signal
228 was calculated using the Hilbert transform (Figure 3, stage VII and VIII). The time of flight
229 was computed using the cross-correlation method and was defined as the peak-to-peak value.
230 The group velocity of Lamb waves was calculated as the distance x divided by the time of the
231 flight. The shape of the dispersion curve was reconstructed by plotting the set of frequencies
232 and corresponding group velocities (Figure 3, stage IX). Employing the group velocity instead
233 of the phase velocity as a quality indicator significantly facilitates the robustness of the
234 developed procedure.

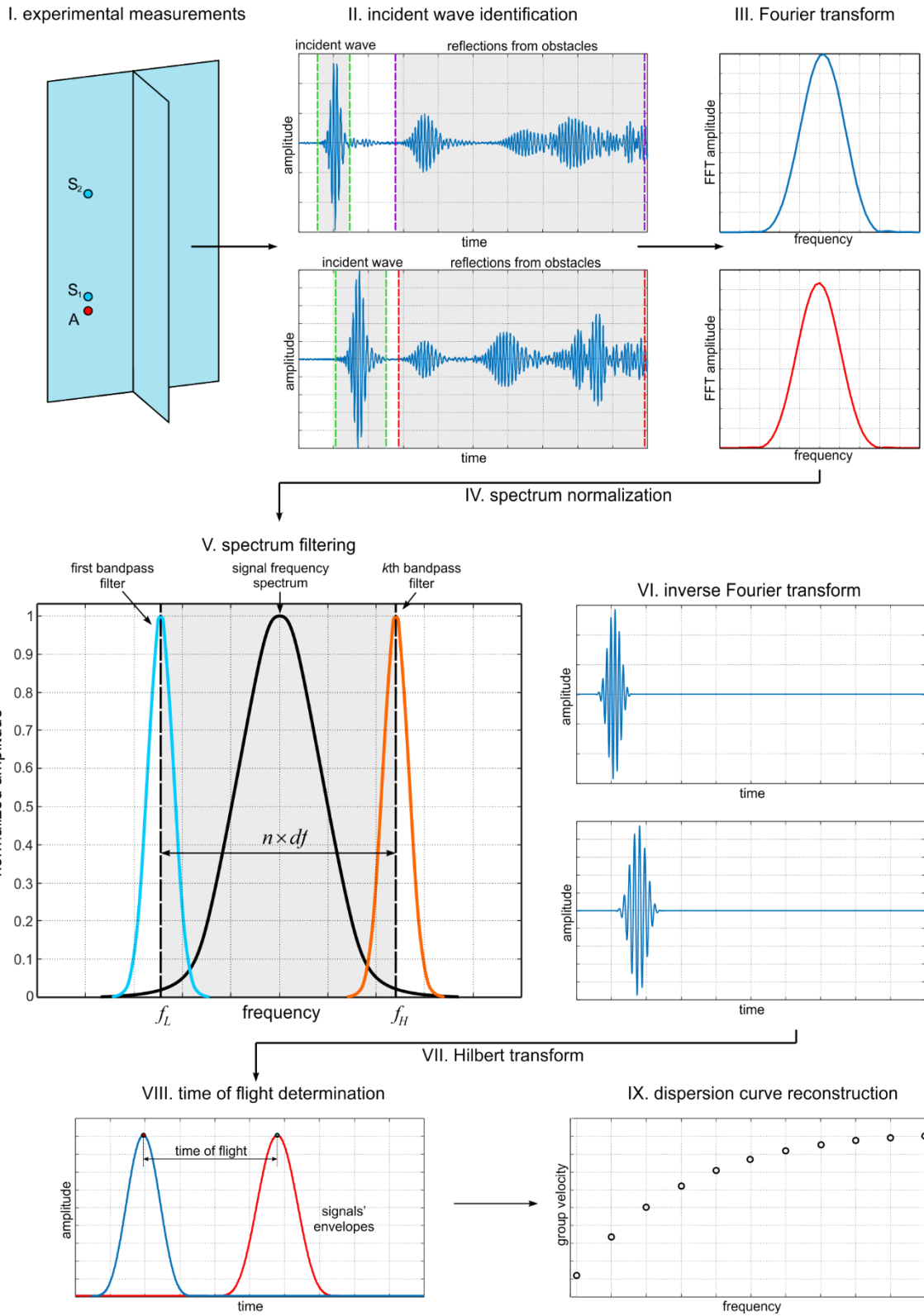
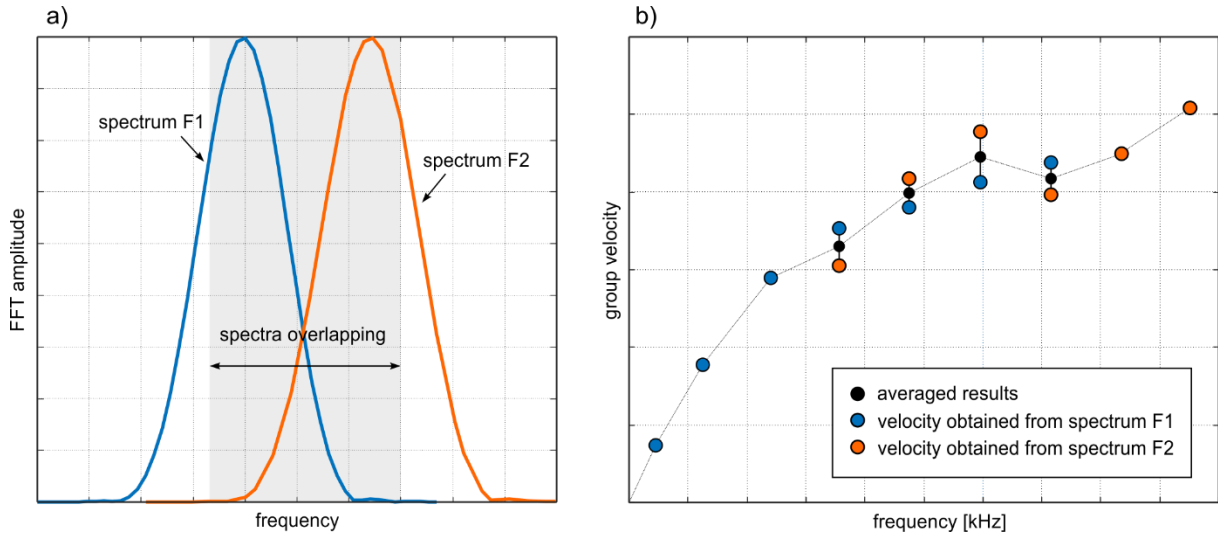


Figure 3 Signal processing procedure

The frequency range within the shape of the dispersion curve can be reconstructed based on the excitation frequency, the width of the signal spectrum, and spectra frequency limits f_L and f_H . In general, the segments of dispersion curves obtained for various frequencies may

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240 overlap (Figure 4a). In such a case, the procedure has been extended by an additional step, and
 241 the group velocity was averaged within the common frequency region (Figure 4b).



242
 243 Figure 4 Processing of experimental data: a) spectra overlapping and b) averaging of group velocity determined
 244 in a common frequency range of both spectra

245 2.3 Identification of corrosion degradation level

246 To estimate the thickness reduction based on the reconstructed dispersion curve, first, the
 247 dependence for the first antisymmetric Lamb mode A_0 was calculated for the pre-established
 248 plate thickness d . Then, the dispersion curve determined numerically based on the analytical
 249 equation was considered as the sets of n pairs of numbers:

$$250 c_{gr}^T(d) = \{(\Delta f, c_{gr}^T(\Delta f)), (2\Delta f, c_{gr}^T(2\Delta f)), \dots, (n\Delta f, c_{gr}^T(n\Delta c_{gr}))\} = \{(\Delta f, c_{gr}^{T,1}), (2\Delta f, c_{gr}^{T,2}), \dots, (n\Delta f, c_{gr}^{T,n})\}$$

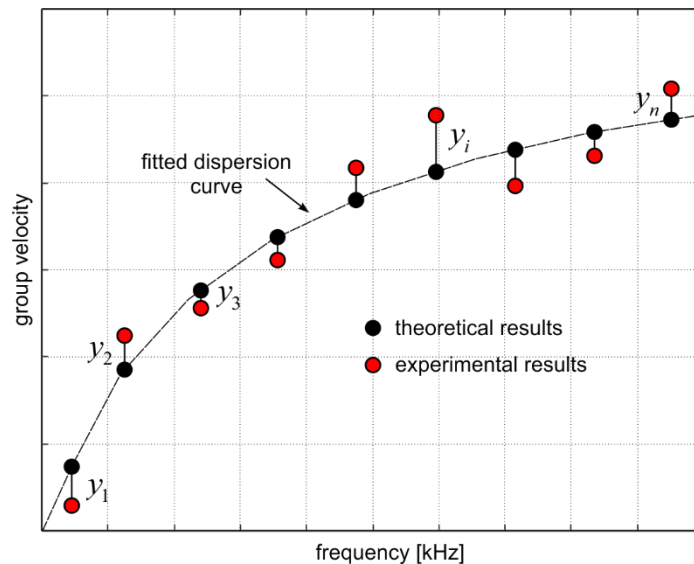
251 The second set of data was obtained from the experimental analysis:

$$252 c_{gr}^E = \{(\Delta f, c_{gr}^E(\Delta f)), (2\Delta f, c_{gr}^E(2\Delta f)), \dots, (n\Delta f, c_{gr}^E(n\Delta c_{gr}))\} = \{(\Delta f, c_{gr}^{E,1}), (2\Delta f, c_{gr}^{E,2}), \dots, (n\Delta f, c_{gr}^{E,n})\}$$

253 Next, the value of the following function has been calculated:

$$254 Y(d) = \frac{1}{n} \sum_{i=1}^n (y_i(d))^2 = \frac{1}{n} \sum_{i=1}^n (c_{gr}^{T,i}(d) - c_{gr}^{E,i})^2 \quad (10)$$

255 The calculations were performed for a varying plate thickness. The function $Y(d)$ reached
 256 the minimum value for the best matching of numerical and experimental dispersion curves
 257 (Figure 5).



258
259

Figure 5 Matching of experimental and analytical results

260 In general, one can say that a similar effect in the form of a dispersion curve can be easily
 261 obtained using different excitation types i.e., broadband pulse excitation providing triggering
 262 multiple frequencies at the same time. This approach has been widely tested in corrosion
 263 assessment applications and its effectiveness in dispersion curve reconstruction based on Short
 264 Time Fourier Transform has been demonstrated. However, the broadband pulse excitation has
 265 several disadvantages which caused to decide to employ narrowband excitation. First of all,
 266 simultaneous excitation of several frequencies is associated with multiple wave mode excitation
 267 and further conversions. In the case of the specimens with more complex geometry and several
 268 modes varying in carrier frequency and velocity, it would be difficult to extract the part of the
 269 signal which should be processed. The second important reason is the possible application in
 270 real monitoring systems. Narrowband excitation associated usually with one single wave mode
 271 is much more effective in the detection of localized damage like corrosion pits or cracks. It is
 272 particularly important as long these two types of corrosion damage can occur simultaneously.
 273 Despite the fact this paper considers only general corrosion, the application of narrowband
 274 excitation potentially allows for both general corrosion degradation assessment (Zima et al.,
 275 2022), as well as the detection and localization of other damage types (Zima, 2021).

276

277 3 Experimental study

278 The experimental analysis of a stiffened steel plate was conducted, which is considered a
 279 primary structural component of the ship hull girder (Figure 6). The analysed stiffened plate
 280 was of 5 mm thickness, and its geometry is presented in Figure 6. The mechanical properties
 281 were determined via tensile tests of coupon specimens according to ISO standard (ISO, 2009).

282 The mean value from seven samples was estimated for the elastic modulus of 198 GPa and
283 yield stress of 272.3 MPa.

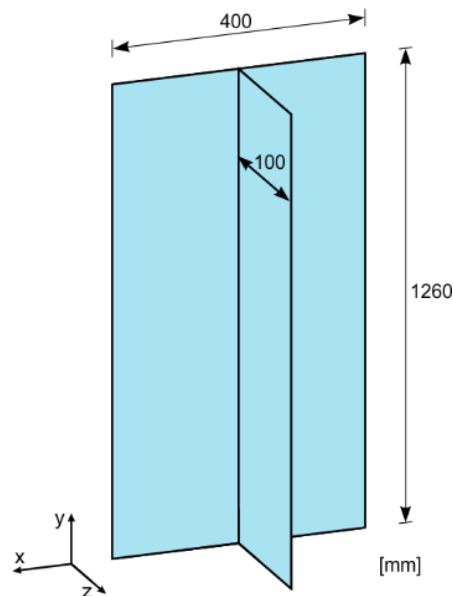


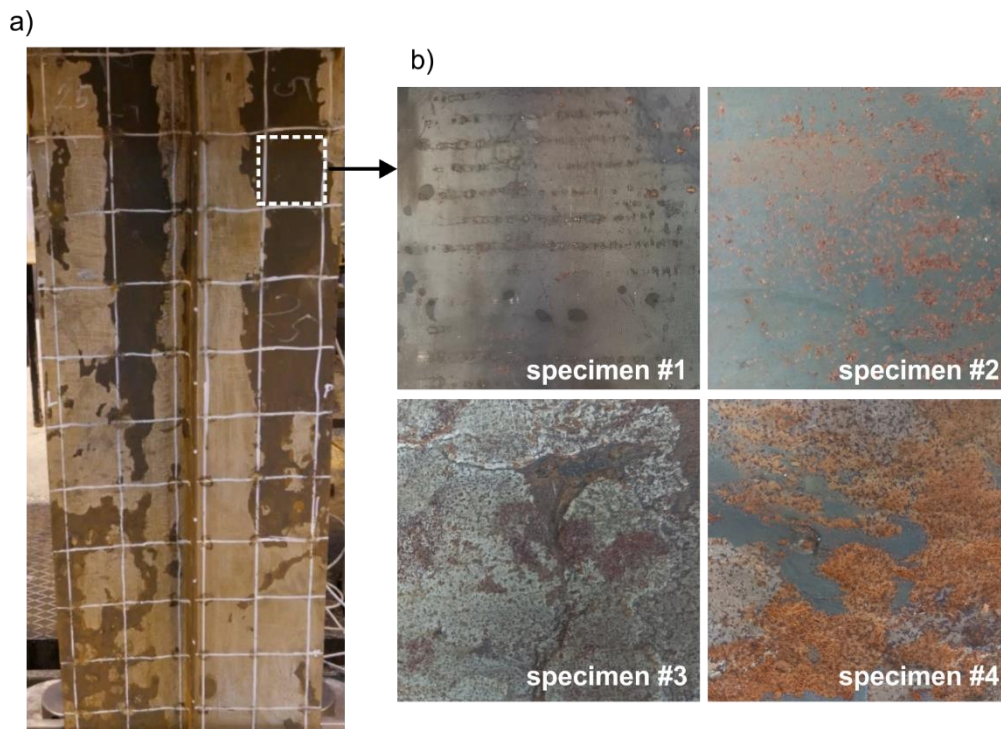
Figure 6. Stiffened plate geometry.

286 3.1 Corrosion degradation

287 The corrosion testing set-up was presented in (Woloszyk et al., 2021), together with the
288 analysis of the generated corrosion degradation. The accelerated marine immersed corrosion
289 degradation was generated by controlling the most important natural factors without applying
290 DC. The specimens were placed in a 900-litre tank made from glass-reinforced plastic. The
291 controlled environmental factors were the salinity (35 ppm), water circulation (induced by the
292 circulation pumps), temperature (approx. 35 °C, increased by heaters), and dissolved oxygen
293 content (augmented by the aeration pump over the limit of fully saturated conditions). The
294 periodical measurements of the stiffened plate specimen's mass were carried out using the scale
295 with an accuracy of 2 g. Based on that, the propagation of each specimen's mean value corrosion
296 diminution with the time was determined. The mean corrosion rate obtained for 5 mm
297 specimens was equal to 0.774 mm/year, and the total duration of the corrosion tests was 428
298 days. In comparison to long-lasting experiments in natural seawater conditions, accelerated
299 testing was a very efficient method. In real ship structures, the mean corrosion rate of the
300 structures does not exceed the level of 0.1 mm/year (Melchers, 2008).

301 Three specimens of an initially 5 mm thickness were corroded, and three different
302 degradation levels (calculated as the percentage loss of the initial mass of the specimen) were
303 generated namely: 7%, 14% and 21%, by pulling the samples out of the water at different times.
304 Although plate surfaces of different initial thicknesses were also corroded, the 5 mm plates

305 were chosen for validation of the new methodology. The thickness variability increased with
306 the corrosion degradation level growth. Figure 7a shows the most severely corroded specimen,
307 while Figure 7b presents the surfaces of any particular specimens.



308
309 Figure 7 Corroded specimens: a) specimen with 21 % degradation level and b) surfaces of corroded specimens

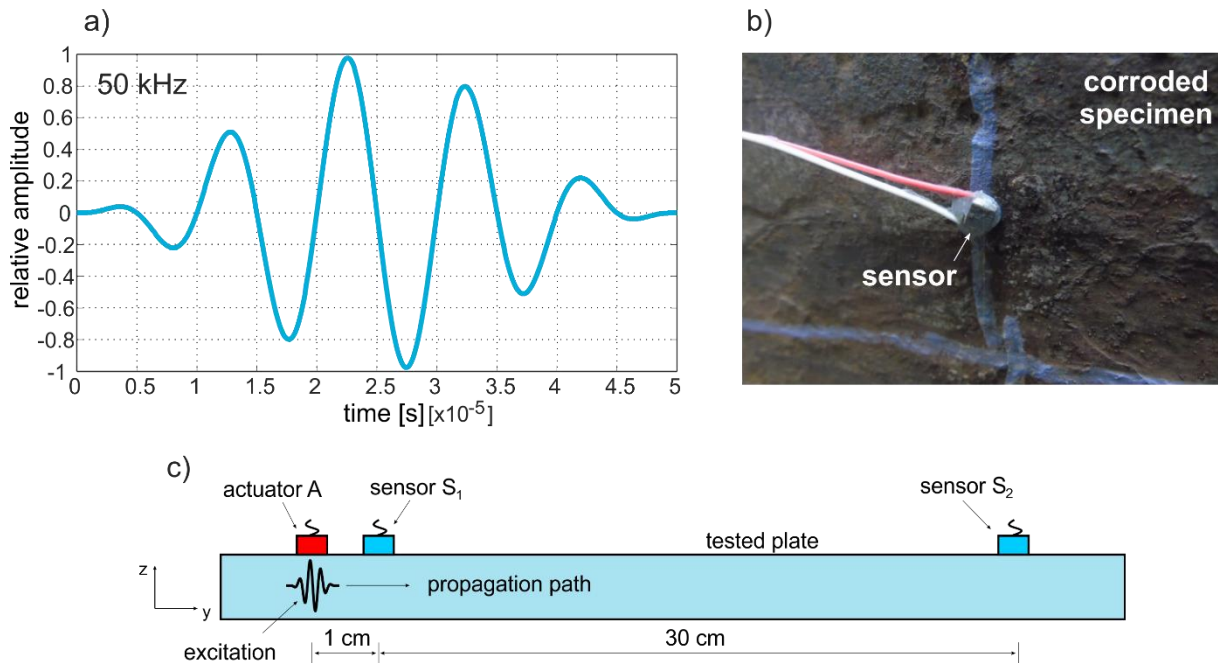
310
311 It must be mentioned here that between environmental accelerated corrosion and the actual
312 corrosion process some differences may occur, especially concerning the internal
313 microstructure of the corroded element. However, the current study is mainly focused on the
314 guided wave-based diagnostics method and recent studies (Zima, 2022) proved that the wave
315 propagation velocity, as well as the time course of the signals, are dependent only on specimen
316 thickness distribution. It means that two specimens varying in geometry but with the same
317 thickness distribution will result in the same velocity and shape of the incident wave. Thus, the
318 speed of the corrosion process has no direct influence on wave propagation signals but the
319 resulting thickness variability and differences in specimen geometry may affect signal
320 characteristics.

321 3.2 Guided wave propagation

322 The excitation and measurements of elastic waves were carried out by an experimental
323 set-up comprised of an oscilloscope, function generator and piezoelectric transducers Noliac
324 NAC2024. To improve the signal-to-noise ratio, the receiver was connected to the high voltage

325 amplifier ThorLab. The Lamb wave excitation was realised as a wave packet consisting of a
 326 five-cycle sine modulated by a Hann window. The carrier frequency was from 50 to 250 kHz
 327 with a step of 50 kHz (Figure 8a). The proposed algorithm has been tested for a low-frequency
 328 range to avoid the excitation of the higher-order modes. The sampling frequency was 500 MHz,
 329 and the input voltage was 20 V. To minimise the influence of electrical noises in the amplifier,
 330 each signal was averaged 1024 times. The perpendicular excitation is associated with triggering
 331 the propagation of flexural waves. Despite that, the presented reasoning is also valid for
 332 symmetric modes, from practical reasons it is much easier to attach the transducer at the plate
 333 surface rather than at the free edge. Therefore, further analysis concerns the antisymmetric
 334 Lamb modes defined by Eq. (1b).

335 The first signal was captured at 10 mm from the excitation source, while the second was
 336 310 mm. The distance x between sensors was 300 mm (Figure 8c).



337
 338 Figure 8 Experimental tests: a) excitation functions and b) sensor attached at the corroded plate surface, c)
 339 configuration of the transducers

340 The waves were propagated along the longer edge of the specimen (the propagation path
 341 was parallel to the stiffener). Such placement of the transducers allowed for avoiding the
 342 interference of reflections from edges and from stiffener with an incident wave which is further
 343 processed. Indeed, the influence of the additional structural elements should be included in
 344 further research. However, because the main aim of the present study is to develop and test the
 345 novel procedure of the corrosion degradation level assessment, we have used the favourable
 346 configuration of the transducers.

347 The reconstructed dispersion curve allows for assessing the corrosion degradation level
 348 along the propagation path. The longer the distance, the greater the monitored area, and the
 349 corrosion's thickness variability will be estimated as an equivalent average plate thickness.

350 The newly developed approach was tested in dispersion curve reconstruction on shorter
 351 distances not exceeding a few centimetres. The short distance minimises the dispersion effects
 352 and allows for a better characterisation of the corroded plate thickness variability as an
 353 equivalent average plate thickness. However, in large-scale offshore or ship structures,
 354 attaching sensors very close to each other would be inefficient. The distance of 30 cm was
 355 chosen to compromise the size of the monitored area of the stiffened plate and the resolution of
 356 the corrosion degradation plate surface roughness. Testing of more extended objects is possible
 357 with adequate amplifying of the excitation. It is also possible to use a different approach like
 358 multiple inputs-multiple outputs and a comprehensive sensor network to increase the monitored
 359 area.

360

361 **4 Analysis and results**

362 Wave propagation signals were processed to estimate the group propagation velocity for
 363 various frequencies and determine the average corroded plate thickness along the propagation
 364 path. The analysis was implemented in a MATLAB environment, and the adopted filtering
 365 parameters are summarised in Table 1.

366 Table 1 Parameters of the Gaussian filters

excitation frequency [kHz]	frequency limits [kHz]		filter bandwidth	filters number
	f_L	f_H	ΔB [kHz]	K [-]
50	35	65	20	11
100	70	130	40	11
150	100	200	50	11
200	130	260	60	11
250	160	330	60	11

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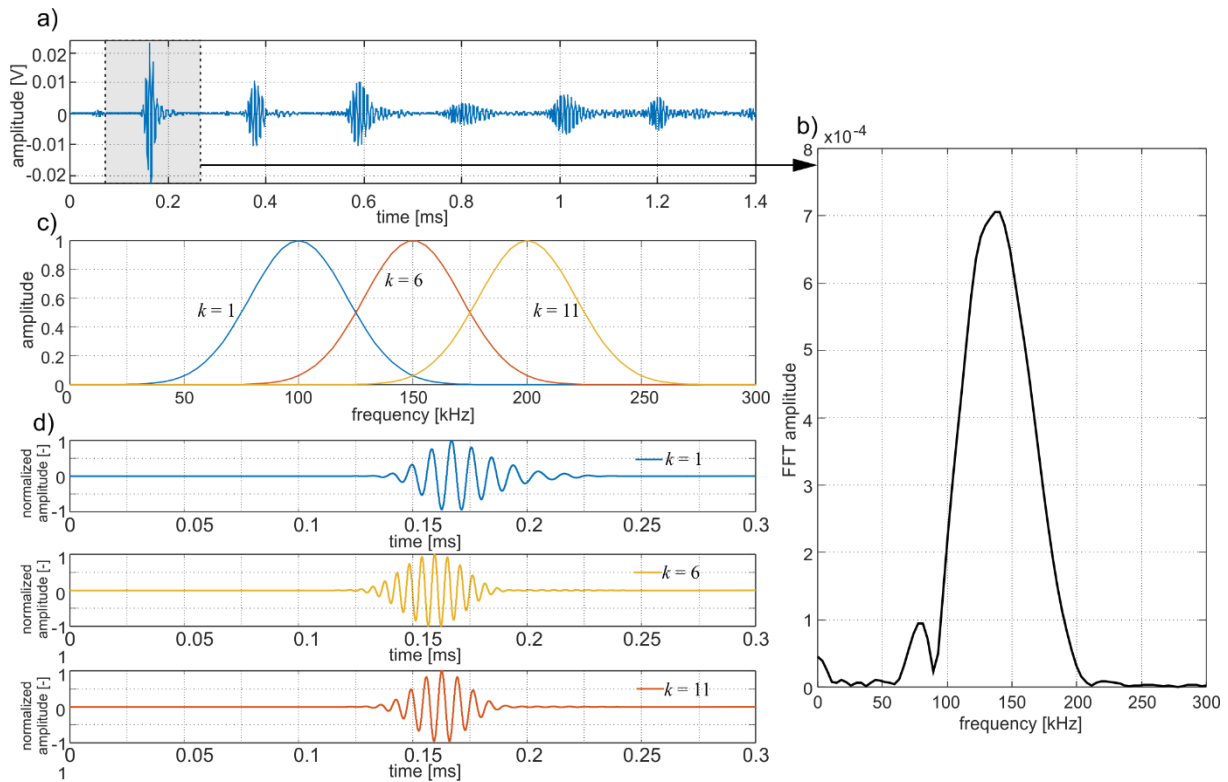


Figure 9 Signal processing: a) registered time-domain signal, b) Fourier transform of the extracted incident wave, c) filters and d) reconstructed signal after filtering

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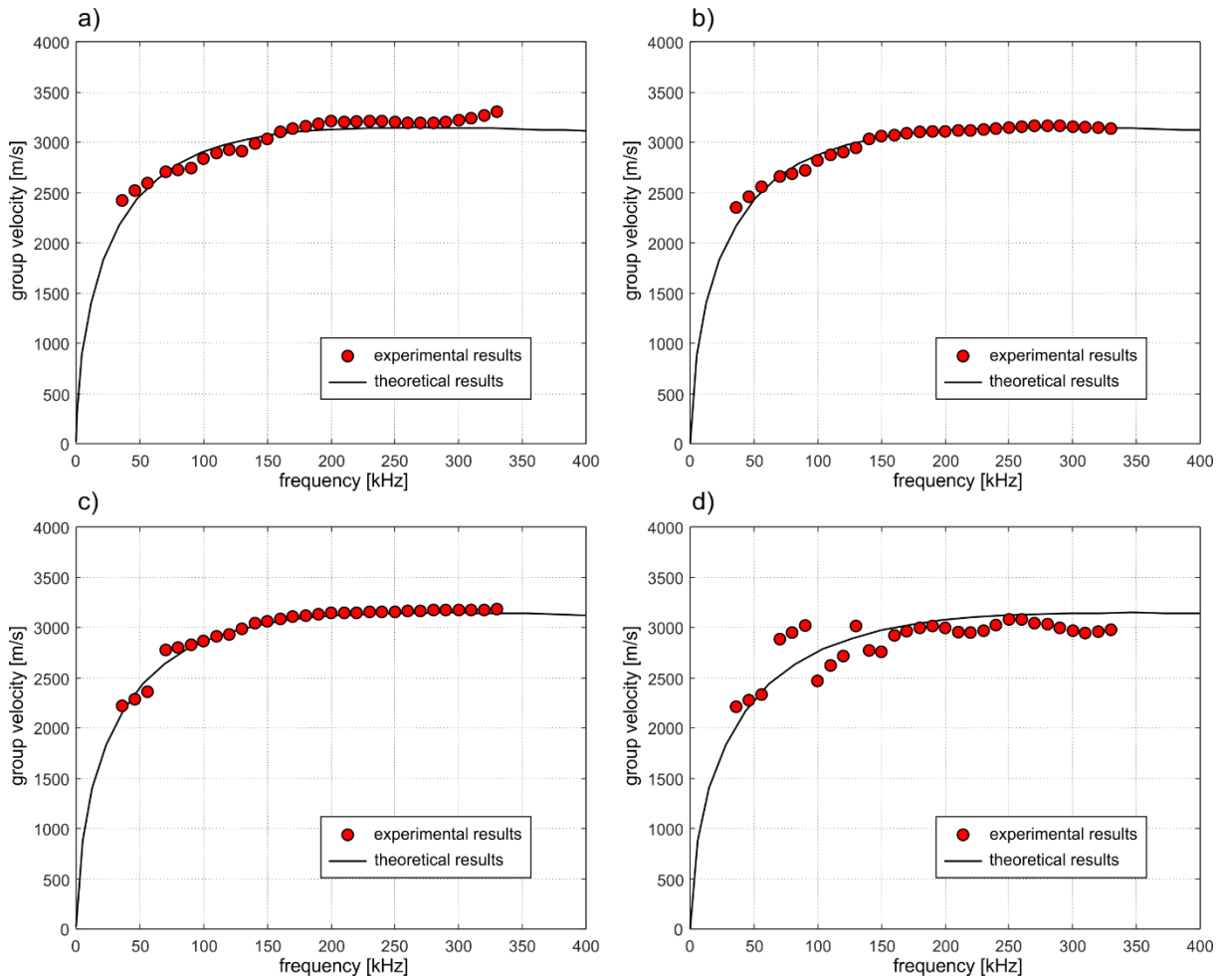
371 An exemplary signal captured by sensor S2 registering for the corroded plate (corrosion
372 degradation level 7%) and the excitation frequency of 150 kHz, as well as the intermediate
373 results in the form of a Fourier spectrum, filters, and three signals obtained for k equals to 1, 6
374 and 11 are presented in Figure 9.

375 The analysis has been divided into two stages. The dispersion curve has been
376 reconstructed within the first stage based on the ten signals registered for five different
377 frequencies. Thus, in total, ten signals were processed. In the second stage, the dispersion curve
378 has been determined based on only two adjacent signals registered for one frequency.

379 4.1 Dispersion curve reconstruction based on several excitation frequencies

380 Figure 10 presents the results of reconstructing the dispersion curves for any particular
381 specimens. Experimental outcomes are denoted by red dots, while the solid black line depicts
382 the Lamb dispersion curve characterised by the minimal value of $Y(d)$ (Eqn 10). Despite the
383 experimental group velocity coinciding well with the dispersion curve, the difference in
384 matching the analytical solution is visible, confirming the correctness of the proposed algorithm
385 of dispersion curve reconstruction. The most significant deviation of experimental results from
386 the theoretical curve was obtained for the specimen characterised by the highest corrosion
387 degradation level (Figure 10d), which the more intense wave integration may cause with

388 irregularities of the corroded surface, as well as with the most significant deviation of the plate
 389 thickness from the average value.



390
 391 Figure 10 Reconstruction of dispersion curves for a) specimen #1, b) specimen #2, c) specimen #3 and d)
 392 specimen #4

393 The estimated parameters of the analysed corroded plates are summarised in Table 2. The
 394 estimated corrosion level C_a has been calculated based on the determined plate thickness from
 395 the fitted dispersion curve:

396
$$C_a = \frac{d_t}{d} \cdot 100\% , \quad (11)$$

397 where d is the thickness of the uncorroded plate determined non-destructively, and d_t is the
 398 thickness of the corroded plate, where d was estimated as 5.18 mm. Comparing the results for
 399 corroded and uncorroded plates, it can be seen that the guided wave propagation approach limits
 400 the inaccuracies of determination of propagation velocity caused by the chosen method of the
 401 time-of-flight calculation and the influence of deviation of material parameters. On the other
 402 hand, the reference signals registered for the original structure are required for such comparison.
 403 Still, it can be noticed that the reference measurement does not have to be made on the same
 404 structure.

405 The estimated corrosion degradation levels differ slightly from the actual one, but a good
 406 agreement between the results is observed. The absolute error, which is defined as the difference
 407 between the accurate and estimated equivalent average thickness:

$$408 \quad e_a = |d_a - d_t| \quad (13)$$

409 did not exceed 0.5 mm, which indicates that the plate thickness may be estimated with high
 410 accuracy even without reference measurements. The maximum value of the relative error
 411 referencing to actual thickness:

$$412 \quad e_r = \frac{e_a}{d_a} \cdot 100\% , \quad (14)$$

413 is equal to 10.42% and was obtained for specimen #3 but is can be explained by the fact that
 414 the general corrosion is not associated with perfect uniform thickness reduction. The higher
 415 corrosion level C_d does not exclude that in some regions the thickness reduction is smaller and
 416 opposite.

417 Table 2 Average corrosion degradation level of stiffened plates

specimen	actual corrosion level C_d [%]	average thickness d_a [mm]	thickness determined by Lamb waves d_t [mm]	estimated corrosion level C_a [%]	absolute error e_a [mm]	relative error e_r [%]
#1	0	5	5.180	0	0.180	2.40
#2	7	4.638	4.890	4.500	0.252	5.43
#3	14	4.320	4.770	6.835	0.450	10.42
#4	21	3.948	4.000	21.875	0.052	1.32

418

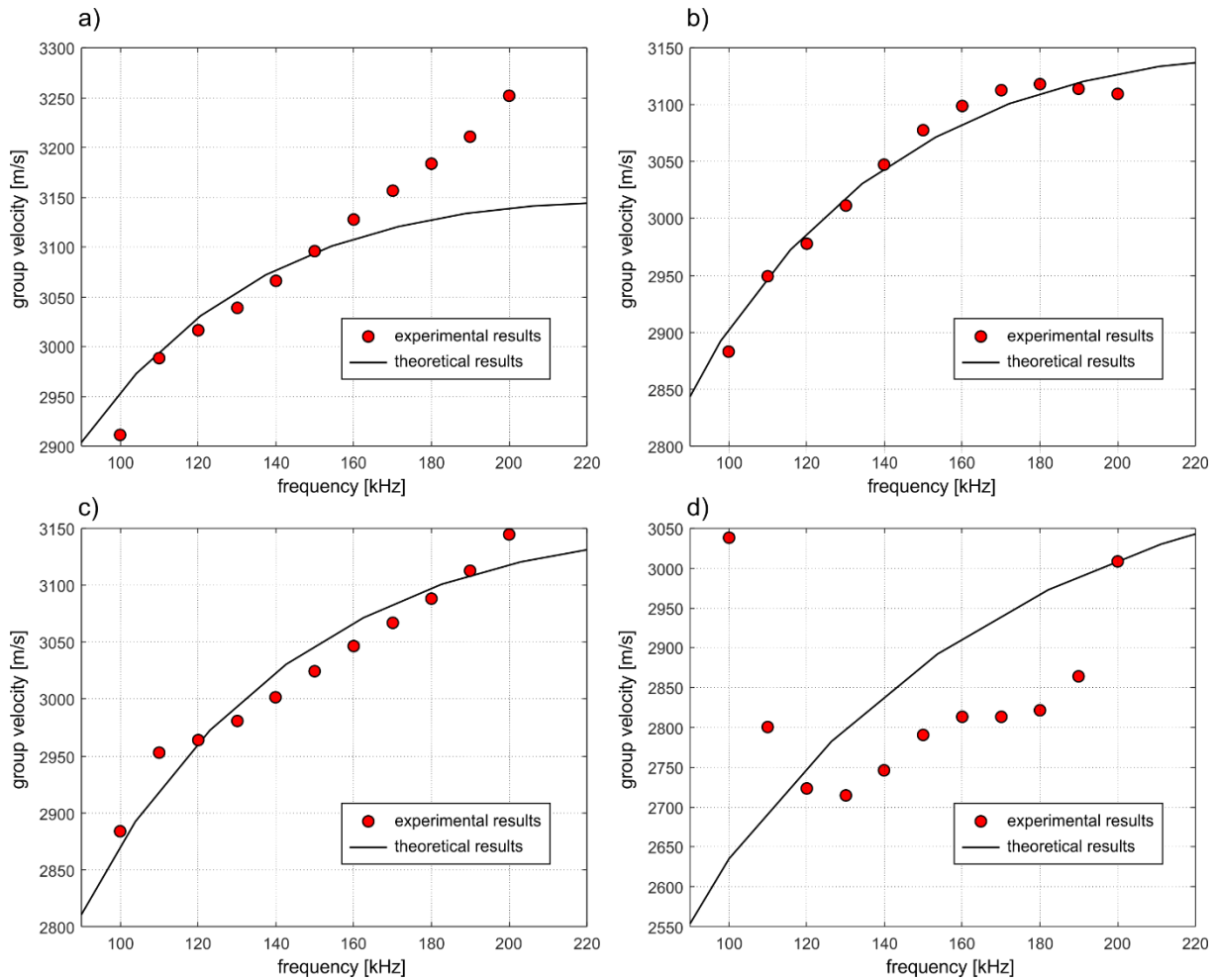
419 4.2 Dispersion curve reconstruction based on one excitation frequency

420 An attempt of corrosion degradation assessment based on one excitation frequency and
 421 only one pair of signals captured at points S1 and S2 were made. The segment of the dispersion
 422 curve has been reconstructed based on the measurement made for an excitation frequency of
 423 150 kHz. Based on the theoretical solution traced for uncorroded plate (Figure 2), one can
 424 conclude that relatively low frequencies (<100 kHz) are highly dispersive, which means that
 425 low-frequency change results in a significant alteration in the propagation velocity.
 426 Consequently, the shape of the propagating wave packet varies significantly along the
 427 propagation path. The potential inaccuracies in measuring the distance between sensors or
 428 calculating the flight time result in a substantial over-or underestimation of the propagation
 429 velocity. Despite that this frequency range seems to be sensitive to plate thickness changes, the
 430 reconstruction of the dispersion curve may be laden with a substantial error.

431 In turn, for the high frequencies (>200 kHz), the dispersion curve becomes flat, the
432 velocity for various frequencies is similar, and the shape of the propagating wave packet
433 remains unchanged. Moreover, the higher the frequency, the shorter the wave becomes and thus
434 is much more sensitive to the surface irregularities caused by corrosion degradation. In the
435 signal, additional reflections are registered, which hinders the unambiguous indication and
436 further extraction of incident waves for the analysis. The wave energy is dissipated faster, and
437 the SNR decreases. Moreover, one can see that the higher frequencies become insensitive to
438 the thickness reduction. The plate thickness reduction is associated with an insignificant
439 propagation velocity change. Considering all aspects mentioned above, a "medium" frequency
440 of 150 kHz is used, which is a compromise between dispersion effects, SNR, and sensitivity to
441 corrosion damage.

442 Figure 11 depicts the experimental group velocities and reconstructed dispersion curves,
443 while the corrosion degradation level assessment is summarised in Table 3. The corrosion
444 degradation level assessment accuracy is lower when the curve is traced based on only one
445 measurement. However, still, a good agreement between actual and estimated corrosion
446 degradation levels was noted. In all cases, the corrosion degradation level has been
447 overestimated. However, the absolute error did not exceed 0.8 mm.

448 The most significant deviations of experimental outcomes from the theoretical solution
449 are observed at the ends of the considered frequency range for the highest and the lowest
450 frequency components of the fundamental antisymmetric mode (100 and 200 kHz). The main
451 reason may be the presence of the side lobes, which were not eliminated from the frequency
452 spectrum despite windowing the input signal and subsequent filtering the Fourier spectrum
453 (Lyons, 2011). The same effect was also observed in the previous investigation stage for other
454 frequencies. Still, the averaging of overlapping curve segments at the ends of the frequency
455 range (Figure 4b) reduced the deviations from the theoretical curve.



456

457

458

Figure 11 Reconstruction of dispersion curves for a) specimen #1, b) specimen #2, c) specimen #3 and d) specimen #4

459

Table 3 Corrosion degradation level of stiffened plates

specimen	actual corrosion level C_d [%]	average thickness d_a [mm]	thickness determined by Lamb waves d_t [mm]	estimated corrosion level C_a [%]	absolute error e_a [mm]	relative error e_r [%]
#1	0	5	5.770	0	0.770	15.40
#2	7	4.638	5.170	10.399	0.532	11.47
#3	14	4.320	4.870	15.598	0.550	12.73
#4	21	3.948	3.290	42.981	0.658	16.67

460

4.3 Calibration and error mitigation

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There are several different sources of inaccuracies where one of the most compelling reasons in the applied approach is the time of the flight. In this study, the time of flight was defined as a difference in the registration time of the peaks of the signal envelopes determined by using the cross-correlation method. However, there are many developed approaches for flight estimation, and the results differ slightly depending on which method was chosen (Xu et al., 2009). Because the thickness was overestimated in most cases, one can conclude a

467 systematic error made during the velocity determination. In the considered frequency range, the
 468 increase of velocity is related to an increase in the thickness. Thus, possibly the applied method
 469 of the time of flight determination based on cross-correlation of the Hilbert transform of
 470 adjacent signals resulted in underestimating the registration time.

471 To investigate whether the systematic error of velocity determination influenced the
 472 results, the following analysis has been conducted: based on the analytical and experimental
 473 dispersion curves obtained for an undamaged plate with a known thickness of $d = 5$ mm., the
 474 error has been determined. The velocity overestimation was $\Delta = 19$ m/s. The velocities obtained
 475 for other stiffened plates have been reduced by Δ , which means that the obtained curves were
 476 just shifted down without changing their shapes, and then the procedure of the corrosion level
 477 identification has been applied (Section 2.3). Table 4 contains the results obtained after
 478 calibrating the velocity based on an uncorroded plate. It is visible that calibrating the velocity
 479 increases the quality of the estimated corrosion degradation level. It is noted, that in most cases,
 480 the presented method overestimates the thickness. However, for Specimen #4, the thickness is
 481 underestimated. At that stage of development, this does not allow to make some general
 482 conclusions regarding that issue and future studies are needed. The error influence may be
 483 limited by conducting the measurements for various frequencies and various distances between
 484 the transducers.

485 Table 4 Corrosion degradation level of stiffened plates after velocity calibration

specimen	actual corrosion level [%]	corrosion level estimated based on Lamb waves [%]	
		without velocity calibration	with velocity calibration
#1	0	0	0
#2	7	10.399	5.200
#3	14	15.598	9.500
#4	21	42.981	20.00

486

487 4.4 Discussion

488 The results presented in the previous section confirm the proposed algorithm's
 489 effectiveness in tracing the dispersion curve and identifying the averaged structural degradation
 490 level. The main advantage over so far presented ultrasonic methods dedicated to thickness
 491 estimation of corroded ship's structural components is the necessity to collect a limited number
 492 of signals. The transducers network does not demand a large number of PZT. The actuator
 493 triggered the signals was captured by two sensors and one actuator placed on a line. The first
 494 sensor should be attached at a short distance from an actuator, which provides a high-amplitude

495 incident wave. The spatial distance between the sensors can be adjusted to the structure size,
496 used equipment, and the desired accuracy of identifying the average corroded plate thickness.

497 A significant advantage is that the presented wave-based method does not require
498 collecting the reference data for an uncorroded structure. The measurements of uncorroded
499 plates improve the quality of the results obtained and allow for better corrosion degradation
500 assessment by reducing the influence of systematic errors, but they are not indispensable.

501 The robustness of the novel procedure was examined in two stages. In the first stage, the
502 group velocity dispersion curve has been reconstructed using signals registered for various
503 excitation frequencies. The main advantage of the approach based on the measurement of
504 several frequencies is that the shape of the dispersion curve can be faithfully reconstructed. On
505 the other hand, the number of required signals and, in consequence, the time of analysis is
506 longer. In the second stage, the signals were registered for only one excitation type. The main
507 advantage of reconstructing only one chosen segment of the dispersion curve is the necessity to
508 use only one excitation frequency for all tested specimens. The assessment of the corrosion
509 degradation demands only two signals be captured at the known distance. However, it also
510 demands the appropriate choice of excitation frequency, which is not a trivial issue and requires
511 considering the shape of the dispersion curve determined based on an analytical equation.

512 Despite promising results, the indispensable prerequisite of the further enhancement of
513 the proposed approach demanded before its practical application is the consideration of its
514 limitations. First, the corrosion degradation identification algorithm does not take into account
515 the plate thickness variability. The corrosion degradation level was indirectly averaged by
516 assuming that the thickness is constant along the propagation path. However, the plate thickness
517 variability can be mapped much better by extending the sensors network or taking additional
518 measurements at other points.

519 The irregularities of the corroded surfaces influenced the quality of the results. The
520 disturbance interactions with abnormalities resulting in wave diffractions and conversions lead
521 to incident wave indication and extraction difficulties for further analysis. Though only one
522 antisymmetric wave mode could propagate within the considered frequency range, wave
523 integration with irregular surfaces might also induce low-energy symmetric wave mode.
524 Propagating of multiple wave packets and their interference affects the shape of the incident
525 wave and, in consequence, the characteristics of the frequency spectrum, which led to
526 inaccuracies in time of flight estimation.

527 The discrepancies between theoretical and experimental results can also originate from
528 the assumption about the constant value of elastic modulus and material density; however, the



529 material parameters are also predefined in standard ultrasonic thickness measurement to
530 calculate the velocity of the pressure wave. Thus, further development of the corrosion
531 degradation level identification algorithm may include the impact on material parameters or
532 fluctuations on the dispersion curve shape. The dependence between wave velocity and any
533 parameter in the dispersion Lamb equation is strongly nonlinear, which means that, e.g., the
534 overestimation of elastic modulus may lead to overestimating wave velocity for one excitation
535 frequency and underestimating for other frequencies. It should be noted that the influence of
536 corrosion degradation on material properties was not considered here. The density, Poisson's
537 ratio, and elastic modulus were assumed the same for all analysed stiffened plates.

538 The next element necessary to consider in further studies is the influence of the additional
539 structural elements affecting wave propagation. The problem of the additional reflections can
540 be solved in two different ways. In general, guided wave-based algorithms are usually used for
541 processing the data collected by specially designed SHM systems. In such cases, signals are
542 measured for various states of the investigated specimen and the reference measurements are
543 available for the investigators. Particular reflections can be identified and interpreted and next
544 excluded on the further stages of monitoring and signal processing. The second way to limit the
545 problem of additional reflections from boundaries and stiffeners is the utilization of different
546 transducer types. Recently, a novel type of frequency steerable transducers has been developed.
547 The novel transducer allows sending of the signal only in one chosen direction, which is
548 dependent on the excitation frequency (Baravelli et al., 2013; De Marchi et al., 2016). The main
549 lobe, characterized by high amplitude propagates in one direction while small-amplitude side
550 lobes propagate in other directions. Even if the total elimination of the boundaries reflections
551 is not possible, their amplitudes can be significantly reduced by focusing wave energy only in
552 an interesting direction.

553 **5 Future perspectives**

554 Since the present study mainly focused on the development of the signal processing which
555 can be potentially used in the SHM systems, several aspects were not considered here and
556 should be investigated in future studies, including:

- 557 • Ships and offshore structures are large in size and complex in geometry. Their
558 diagnostics would require a more complex sensor network. The optimal sensor
559 placement will be considered. The trade-off between the resolution and extent of the
560 sensors network must be considered.
- 561 • Practical application of the developed approach requires considering the reliability of the
562 proposed method and the influence of inaccuracies on the determined DoD (Falcetelli et

563 al., 2021). This should in particular cover further studies regarding higher thicknesses of
564 analysed plates and related uncertainty levels.

565 • Guided waves are widely used for localized damage detection. Therefore, the possibility
566 of building multi-step algorithms for both general uniform and pitting corrosion detection
567 and evaluation must be investigated.

568 **6 Conclusions**

569 This study conducted theoretical and experimental investigations of guided wave
570 propagation in corroded stiffened plates. The newly developed approach allows for an average
571 corrosion degradation level identification based on the single measurements of the tested
572 stiffened plates.

573 The experimental data acquired for four different stiffened plates varying in degradation
574 level confirmed the correctness of the developed procedure of dispersion curve reconstruction.
575 The corrosion degradation level identification has been made in several different ways: once
576 the dispersion curve has been traced based on several measurements made for various
577 frequencies. At the same time, in the second case, the signals were captured for only one
578 excitation type. It was proved that the corrosion degradation level was better assessed if the
579 measurements involved a wider frequency range. However, regardless of the considered
580 frequency range within the dispersion curve that has been reconstructed, the corrosion
581 degradation level remained slightly underestimated, which indicated the possible systematic
582 error related to the time of flight and, in consequence, with group velocity estimation. Based on
583 the assumption that the initial thickness of the uncorroded stiffened plate is usually known a
584 priori, the value of systematic error has been established and included in further assessing the
585 corrosion deterioration of other stiffened plates. It allowed for a better estimation of the precise
586 degree of corrosion degradation.

587 The highest deviation between experimental measurements and theoretically defined
588 dispersion curve was observed for the most severely corroded stiffened plates. This allows the
589 hypothesis that the presented methodology could determine the average thickness and its
590 variability level. After further development, the proposed method should be applicable in all
591 cases requiring multiple ultrasonic measurements to assess the thickness of steel structural
592 elements.

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596

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