Non-Destructive Evaluation of Cooperative Structures (NDECS): A Third Way?

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ABSTRACT

SHM is born from the conjunction of several techniques and has common basis with NDE. In fact, several NDE techniques can be converted into SHM techniques by integrating the sensors and the actuators inside the monitored structure. NDE is mature, since several decades of research and development have been made. Contrariwise, SHM just begins to come out from laboratories, and applications at a wide scale remain a long-term objective. In these conditions, we may wander if an intermediate way, less performing but feasible at a shorter term, would not be an attractive and relevant position.

This third way consists in only embedding at well-chosen locations into the structure the stimulation (actuators or emitters) and leaving the detection (receivers or sensors) outside. To optimize such a system, Lamb waves could be used for the emission and full-field real time imaging techniques used for the reception. So, using the more recent and promising techniques of both domains - SHM and NDE -, the proposed technique could be applied at a short term, with existing technologies and would permit time and money saving for maintenance operations. A well-suited appellation for this type of technique could be: Non-Destructive Evaluation of Cooperative Structures (NDECS).

The principle and first validation experiments of two possible NDECS systems, stroboscopic shearography and lock-in ultrasonic vibrothermography, imaging Lamb waves generated by embedded piezoelectric patches, are presented.

INTRODUCTION

The recent evolution of Non-Destructive Evaluation (NDE) techniques used for the maintenance of structures is characterized by rapid and dramatic changes. These changes also concern the general philosophy of structure maintenance and monitoring.

Three major evolutions can be highlighted:

-in the pure NDE field, the ever growing importance of full-field real-time imaging techniques;

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- the birth and the impressive development of Structural Health Monitoring, which could be superficially considered as an avatar of NDE, if only seen as a fully integrated NDE;
- the importance taken by the use of Lamb waves to elaborate SHM systems.

The first section of the lecture is a reflection on this evolution, based on a literature survey and on our own experience at ONERA (French Aerospace Research Agency). Details are given for illustration.

This reflection will lead us in section 2 to consider a possible third way, intermediate between NDE and SHM: Non-Destructive Evaluation of Cooperative Structures (NDECS).

Sections 3 and 4 describe two possible NEDCS and present laboratory results demonstrating their feasibility. In both cases, the techniques presented result from the combination of Lamb wave generation thanks to embedded or surface mounted piezoelectric patches and of full-field real-time imaging of the interaction of these waves with damages existing in the structure.

RECENT EVOLUTION IN NDE, SHM AND MAINTENANCE PHILOSOPHY

Evolution in NDE

Until now, the maintenance of aerospace structures is based on the use of non destructive evaluation techniques. These techniques are in constant evolution thanks to numerous research and development works. The best source of information on these works is certainly the collection of proceedings entitled: “Review of Progress in Quantitative Non Destructive Evaluation”, annually published since 25 years [A].

One of the characteristic evolutions of NDE and of experimental mechanics techniques is the importance taken by the development of full-field real-time imaging techniques. Such techniques, thanks to CCD cameras, are in fact performing a parallel acquisition of data information coming from a very large number of locations. This is achieved by cameras working in various spectral domains: ultraviolet, visible, near or far infrared, associated with coherent light illumination (interferometric optical techniques like Electronic Speckle Pattern Interferometry [1]) or not (stimulated thermography [2], visible image correlation techniques [3]…). These techniques can image fields of displacements, deformation, temperature… of structures submitted to various types of solicitations: loads [4], fatigue [5], vibrations [6,7], radiant energy deposition [8,9], eddy-current [10], electromagnetic fields [11], etc. Sometimes the imaging technique is based on a more subtle effect, like the Faraday effect (influence of a magnetic field on the optical index) used to image the interaction of eddy-current with a defect like a crack in metallic structure [12].

A high-frequency periodical excitation often used in NDE consists to propagate ultrasounds in the structure. It is the most popular NDE technique. Nevertheless, it has been only very recently coupled to full-field imaging techniques, and more particularly with shearography and thermography. This will be examined in sections 3 and 4.

Evolution in SHM

Birth of a SHM community

In fact, SHM, which belongs to the domain of smart materials and structures R&D, can be considered as a new form of NDE, characterized by the full integration of sensors, actuators and intelligence inside the structure during its manufacturing process. It is the reason why the recent SHM community growth is partially explained by the progressive aggregation of members of the NDE community, while SHM, at its beginning, was mainly issued from the mechanical engineering community.

SHM techniques appeared in the nineties and show an impressive development [4]. The growing community of SHM production can be found in proceedings of specialized conferences totally devoted to SHM and covering all fields of applications [B, C, D, E, F] and in some conferences on NDE or on Smart Materials and Structures which now include sessions on SHM. Regarding scientific journals, the same scheme exists: the SHM works are published in a really specialized journal (SHM Journal) and in journals linked to NDE, smart materials and structures, control, aerospace, civil engineering… It is clear that the creation of both journals and conferences fully devoted to SHM strongly contribute to the birth and development of the SHM community.

Importance taken by Lamb waves and piezoelectric sensors/actuators

Now, if we look carefully at the SHM literature we see an increasing importance of Lamb wave based works and for this purpose a quasi universal use of piezoelectric patches. To illustrate these two facts, figures 1 to 4 present statistical data based on a study of the SHM literature over the period 1997-2003. For this study, 1150 papers or communications have been analyzed.

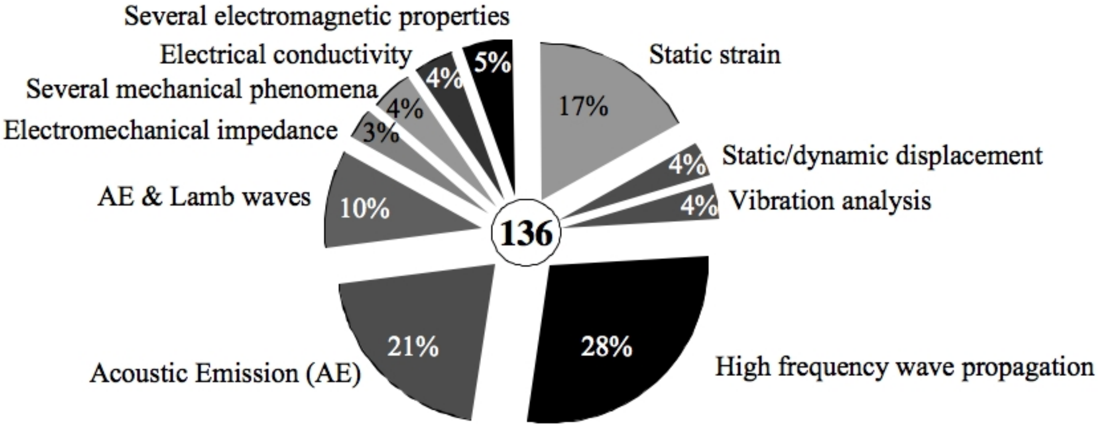


Fig. 1 – Methods used for the monitoring of delaminations in composite structures, from [4]. The number at the center of the graph is the number of references considered for the statistical analysis. This remark is valid for figures 1 to 4.

Figure 1 presents the different methods used to detect delaminations in composite structures. The graph shows that 28% of the works deal with high frequency wave (essentially Lamb waves) propagation, 10 % consider system able to analyze both Lamb wave propagation and acoustic emission (which in fact is mainly composed of Lamb waves), and that acoustic emission detection is considered by 21 % of the works. If we add the use of electromechanical impedance technique, we obtain for the sum of this family of techniques a total of 72%. If we just consider active systems able to detect Lamb waves, the sum of the first two categories represents 38% of the total. Since 2003, we can also state that the relative importance of this technique has increased.

Correlatively, the use of piezoelectric sensors has a prominent position, at least for composite structure applications. Figure 2, taken from the same reference [4] presents the distribution of the types of sensors used. The graph shows that 68% of the works use piezoelectric transducers. Among them 65% deal with PZT single patches, 16% with matched patches, to generate beam forming, and 4% are devoted to the SMART layer which consists in piezoelectric sensor nets pre-positioned on a dielectric thin film.

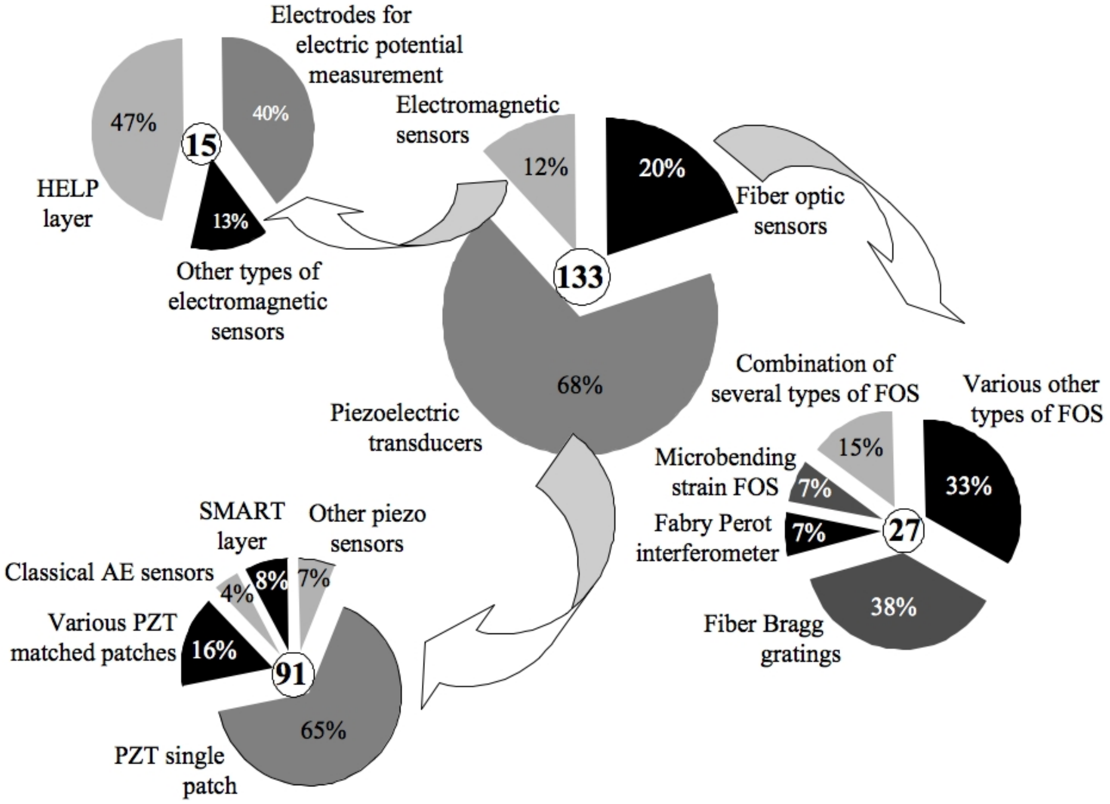


Fig. 2 – Type of sensors used for the monitoring of delaminations in composite structures. Statistics based on a general survey of SHM literature for the period 1997-2003 (1150 references), from [4].

For the detection of cracks in metallic structures, the results are similar (see Figure 3): 52% of the works are based on Lamb wave propagation and 55% use piezoelectric transducers.

Of course, the situation is totally different if we consider civil engineering, the other important domain of application. In this domain, piezoelectric sensors and Lamb waves have a weak importance. This explains why if we consider the whole papers and communications, whatever be the field of application, the importance of piezoelectric transducers is lower, although still at the first rank (see Figure 4).

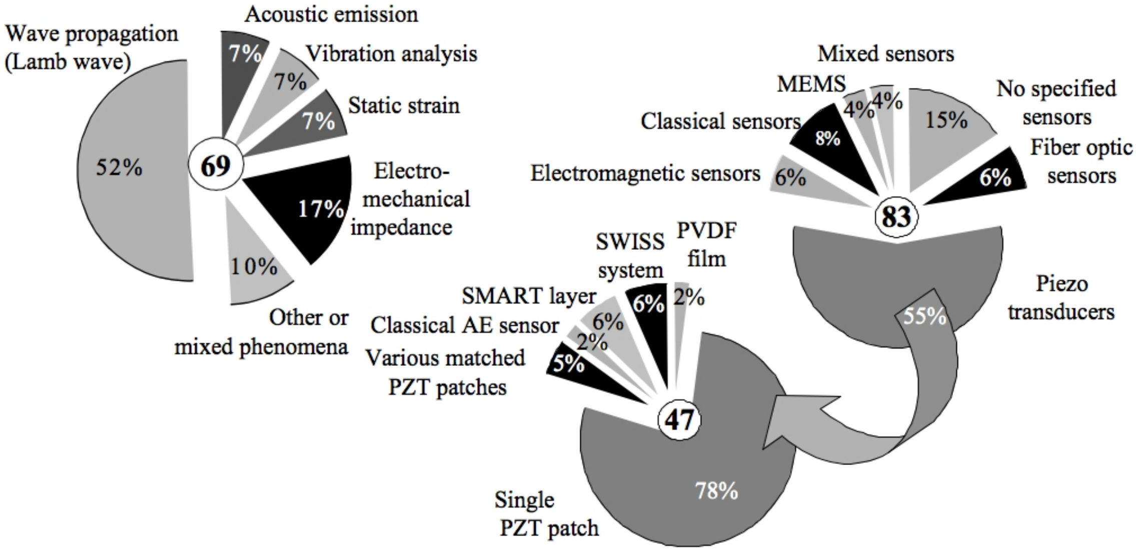


Fig. 3 – Same statistics as in Figure 1 and 2, but for the monitoring of cracks in metallic structures. On the left: methods used; on the right: sensors used and detailed analysis for piezoelectric transducers.

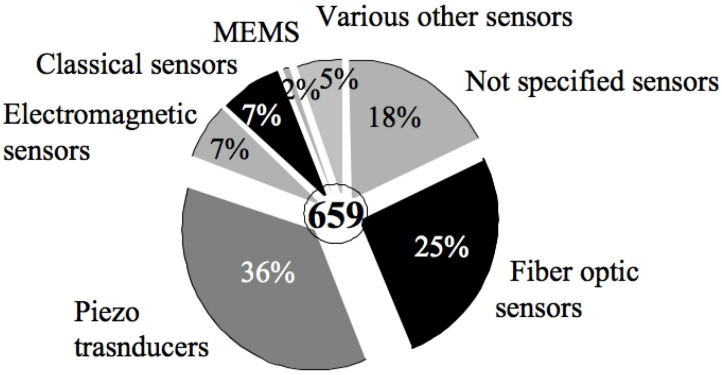


Fig. 4 – Types of sensors used when considering the full literature (including civil engineering applications).

Maintenance philosophy

The three evolutions previously described (growing importance of full-field real-time imaging techniques, impressive development of Structural Health Monitoring, importance taken by the use of Lamb waves to elaborate SHM systems) are mainly driven by a cost-reduction strategy of maintenance operations (short term objective). The second evolution – development of SHM - aims to the replacement of scheduled maintenance inspections by performance-based or condition-based inspections (long term objective).

The introduction of SHM is a revolution which changes the philosophy of maintenance and this will affect the full organization of large systems. In fact, Health monitoring, coupled with Usage and Condition Monitoring, and with the help of predictive models for material behaviors, will permit a real Health Management. This long term evolution is described elsewhere [13-15].

BETWEEN NDE AND SHM COULD WE IMAGINE A THIRD WAY ?

We see that, presently, there are two axes of research and development:

- Improvement of NDE techniques to make the classical approach more efficient and less costly – short-term objective -,
- Development of the SHM approach to satisfy both this short term objective, and to reach a more ambitious long-term objective.

If we consider the progress achieved in both NDE and SHM field and described in the preceding section, a third approach seems now possible. This third way could consist in only embedding at well-chosen locations into the structure the stimulation function (actuators or emitters) and leaving the detection (sensors or receivers) outside. To optimize such a system, Lamb waves could be used for the emission and full-field real time imaging techniques used for the reception. So, using the more recent and promising techniques of both domains - SHM and NDE -, the proposed approach could be applied in a short term, with existing technologies and would permit time and money saving for maintenance operations. A well-suited appellation for this type of technique could be: Non-Destructive Evaluation of Cooperative Structures (NDECS).

Such an idea is not totally new. A similar approach has been proposed by Walsh [16] with a more limited field of application. In this reference it is proposed to replace conventional ultrasonic testing using surface contact probes by a semi embedded system in which the emitter is inside the structure and the detector is outside, which allows an improved resolution and a large depth of penetration. Figure 5, taken from this reference, illustrates the concept, which was called by the author: Non Destructive Evaluation Ready Material (NDERM). The NDECS concept here proposed is more efficient and more ambitious.

Figure 6 presents a schematic view of what could be a NDECS system. Two versions are described, one using stroboscopic shearography to monitor the full-field of surface displacements created by the Lamb waves generated by the embedded emitter, the other using lock-in thermography to monitor the thermal effects resulting from the interaction of the waves with possible damages like delamination, cracks or corrosion. These two imaging techniques are chosen because they seem the more promising and they are almost ready to be used, since the feasibility has been proven in the laboratory.

The following two sections will present in details the principle and some laboratory results already obtained at ONERA using these two NDECS techniques.

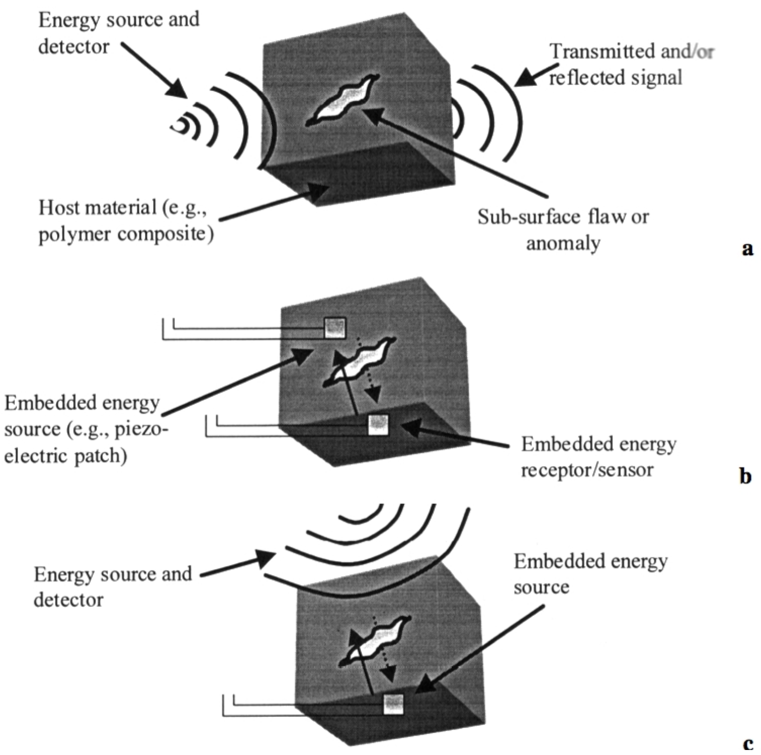


Fig. 5 – The Non-Destructive Evaluation Ready Material (NDERM) concept proposed by Walsh: a) Conventional ultrasonic (surface contact) NDE, b) Smart material with active and passive embedded sensors, c) NDECS: embedded elements improve resolution and depth of penetration of conventional ultrasonic NDE system. Image taken from [16].

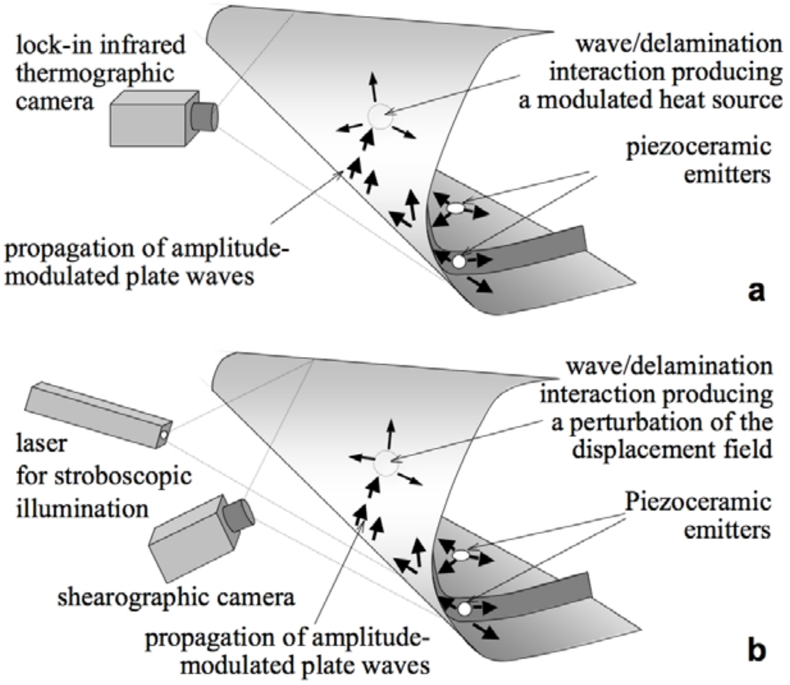


Fig. 6 – Two possible NEDCS: a) ultrasonic vibrothermography with Lamb waves generated by embedded piezoelectric emitters, b) shearographic visualization of Lamb wave interaction with damage.

IMAGING LAMB WAVES INTERACTION WITH DAMAGES USING STROBOSCOPIC SHEAROGRAPHY

Shearography is a relatively well-known optical NDE technique. Nevertheless, its application to ultrasounds imaging requires a special procedure. This procedure has been very recently introduced and remains slightly known. In this section we will recall the principle of shearography and presents how we can use it to image ultrasounds. Then, illustrative examples obtained at ONERA will be presented demonstrating their good ability to detect and characterize damages.

Principle of shearography

Shearography is a speckle interferometric technique appeared in the seventies [17-19]. Its principle is shown in Figure 7 left. The coherent light reflected by the structure under test does not interfere with a reference beam like in classical holographic techniques, but with itself, thanks to an optical shear obtained by a device like a Michelson interferometer with a tilted mirror. This permits to be insensitive to ambient vibrations, making the technique applicable in industrial conditions. The measurement is performed for two successive states of deformation of the structure. By electronic data reduction a subtraction of the two

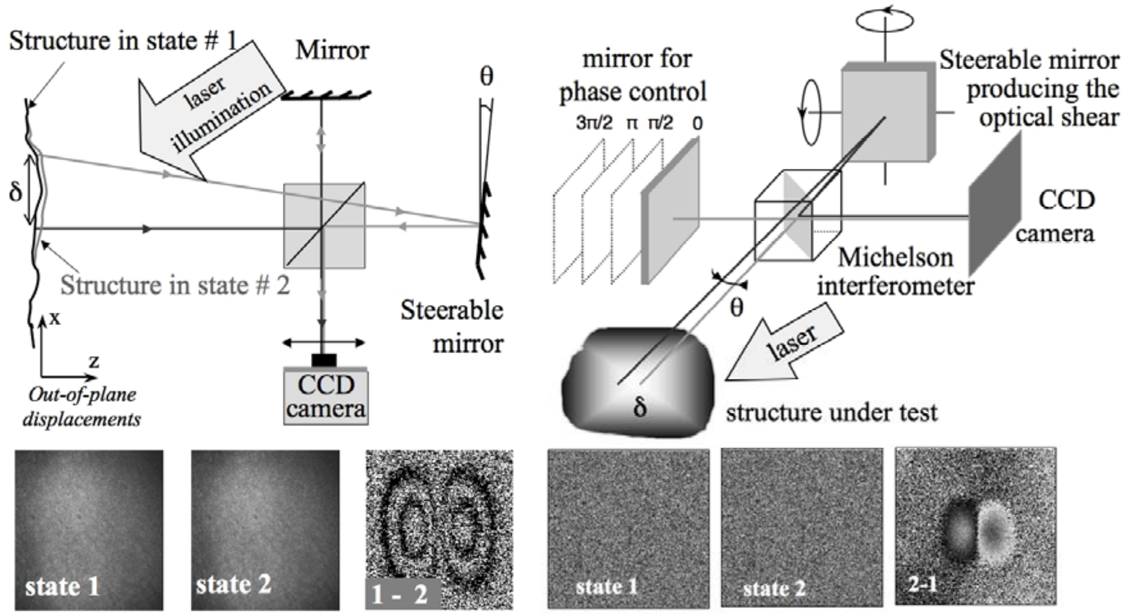


Fig. 7 - Principle of shearography using a Michelson interferometer (upper left). At the lower left are given the speckle intensity images corresponding to the two states of the structure and the pseudo-fringes image resulting from their difference and presenting an intensity linked to the variation of the difference of phase between two points of the structure separated by a distance equal to the shear distance δ. On the right, a set-up for quantitative shearography, allowing to introduce phase shifting (phase stepping) in the arm of the interferometer, is presented. From four intensity images of the same state corresponding to phase lags of 0, $\pi/2$, π, and $3\pi/2$, a phase image is calculated (lower right) and from the difference of the phase images corresponding to the two different states of the structures a final differential phase image is obtained giving the difference of phase (and correlatively the difference of z-displacement) between two points of the structure separated by a distance equal to the shear distance δ.

speckle images produces a resulting image containing information linked to the gradient of deformation between the two states in the direction of the shear. To make the technique quantitative a phase stepping is required and from four intensity images corresponding to four phase lags introduced thank to the mobile mirror (see figure 2 right) a phase image is obtained which can be directly graded in gradient of deformation. The final result is the third image of figure 7 lower right which corresponds in the present case to a bump in the surface. This image put in evidence the difference between shearography and more classical interferometric techniques like Electronic Speckle Pattern Interferometry (ESPI) which directly give the field of deformation [1].

To produce two different states of deformation of the structure it is possible to use depressurization [20, 21], photothermal stimulation [21, 22] or vibrations. In the late case, to define two states, it is necessary to produce a stroboscopic illumination with an acousto-optic modulator in the laser beam [23] as seen in Figure 8a.

Principle of the shearographic imaging of ultrasounds

Gordon and Bard [24] were the first to propose and to apply this technique to the visualization of ultrasounds. As shown in Figure 8b the two states of deformation of the structure correspond to two laser illuminations with a phase difference of 180° with respect to the ultrasounds. The phase stepping technique is used (Figure 8c) and, to increase the signal to noise/ratio, for every phase shift, image accumulation is performed during 20 ms.

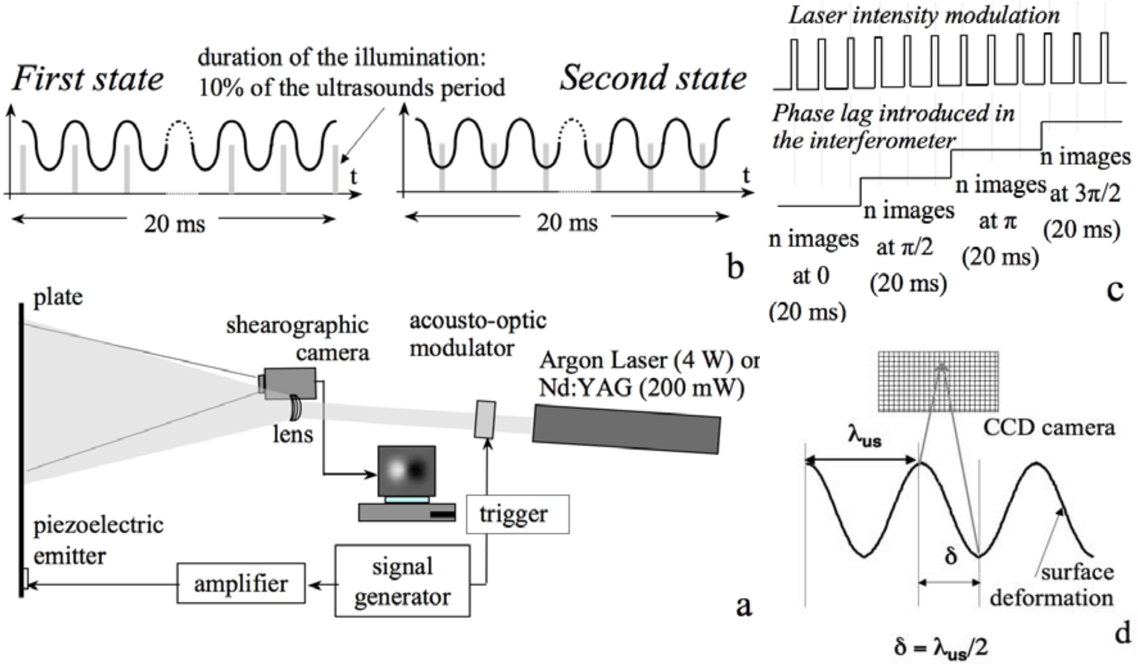


Fig. 8 – Visualization of Lamb waves by shearography: a) experimental set-up (the shearographic camera contains the three elements of the Michelson interferometer: shearing, phase stepping and shear control devices. b) synchronization between the signal feeding the emitter and the laser illumination, producing the stroboscopic effect. c) synchronization between the laser illumination and the phase lag introduced in the arm of the interferometer (valid for the two states). d) shear adjustment (shear distance equal to half the wavelength).

Finally, the better sensitivity is obtained with a shear equal to half the ultrasound wavelength (see Figure 8d) producing a difference of displacement between the two interfering points which is maximum. In these conditions, the shearographic image level is strictly equal to four times the ultrasound amplitude, with sensitivity of the order of one nanometer. If the shear is equal to the wavelength, then the wave is not seen, the deformation of the interfering points being identical, which can be interesting to visualize the waves diffracted by a damage [25, 26].

The use of continuous Lamb waves leads to results which can be hard to interpret if natural elements are likely to induce reflections, mode conversions... Such elements can be fasteners, stringers, rivets... or simply the plate edges. In particular these effects are important in metallic structure for which the attenuation of Lamb waves is very low. To avoid this inconvenient, it is more convenient to generate short bursts and to follow their propagation [26,27]. Some modifications had to be introduced relatively to the wave imaging mode: only one laser stroke is used per burst and its firing is delayed according to the propagation stage one want to image. The second surface state is simply obtained by reversing the transducer input voltage.

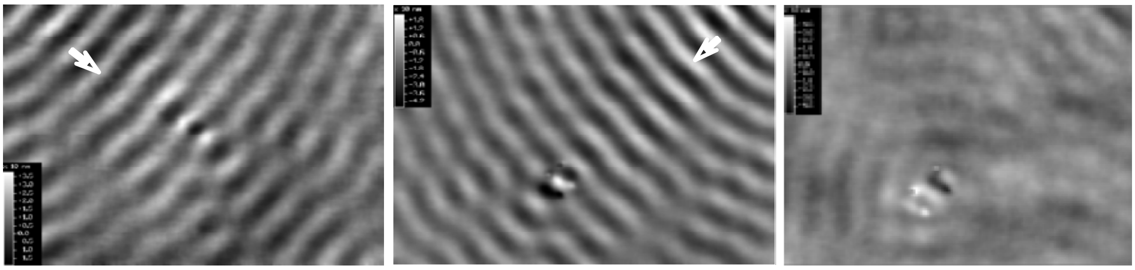
Finally let us remark that, in its simplest way of application, the shearographic camera is viewing the structure perpendicularly to its surface, and then only the out-of-plane displacement is detected. This is the case of the results here presented. Nevertheless, it is possible to visualize the in-plane displacement, and this can be useful for Lamb wave imaging [28,29].

Illustrative examples of shearographic imaging of Lamb waves

The technique is particularly interesting to use with Lamb waves which propagate on long distances. This give more reasons to use such a large field visualization technique. This is the reason why ONERA largely used the technique since the end of the nineties. The technique is particularly useful in the research phase to better understand the interaction phenomena, in particular when the structure is complex.

Figure 9 presents the visualization of the interaction of Lamb waves (anti symmetrical fundamental mode S_0) with a delamination in a C/epoxy plate [25,26,30]. The detection and localization are unambiguous and feasible on both front and rear faces of the plate (the front face being the outside face submitted to the impact). The interaction between the incident wave and the delamination is a diffraction phenomenon. It is possible to detect, although not so easily, this diffraction (emergent wave) around the damaged area (in particular in the left image). These images were obtained with surface-mounted thin circular PZT patches.

Figure 10, taken from [31], presents an interaction in a more complex configuration: an artificial defect in a composite sandwich structure of a radome. The defect is a lack of material, representative of a disbond between the outer skin (glass/epoxy composite) and the core made of low density foam. It is interesting to note that there is an interaction only in the outer skin which is debonded, which allows us to delimit the damage extent. No interaction is produced in the inner skin, which is thicker, because its dispersion curves are almost identical to that of the full sandwich. The damaged area seen on the shearographic image has the real shape (triangle) of the void in the core.



a b c

Fig. 9 – Interaction of Lamb waves (S_0 mode, 68 kHz) propagating in a $[0_4/ 45_4/ 90_4/- 45_4]_S$ C/epoxy plate of dimensions 70x70 cm^2 with a delamination produced by a 5 J impact. The dimensions of the images are 17x12 cm^2 and their dynamic range is near of 50 nm. The electric power injected in the piezoelectric emitter (disc-shaped, 30 mm in diameter and 200 μm thick) is equal to 1 W (from [25, 26]). Successively: a) front-face, shear distance equal to half the wavelength, to show both incoming and diffracted waves; b)idem for rear-face; c) rear-face, with a shear equal to the wavelength, to just show the diffracted waves.

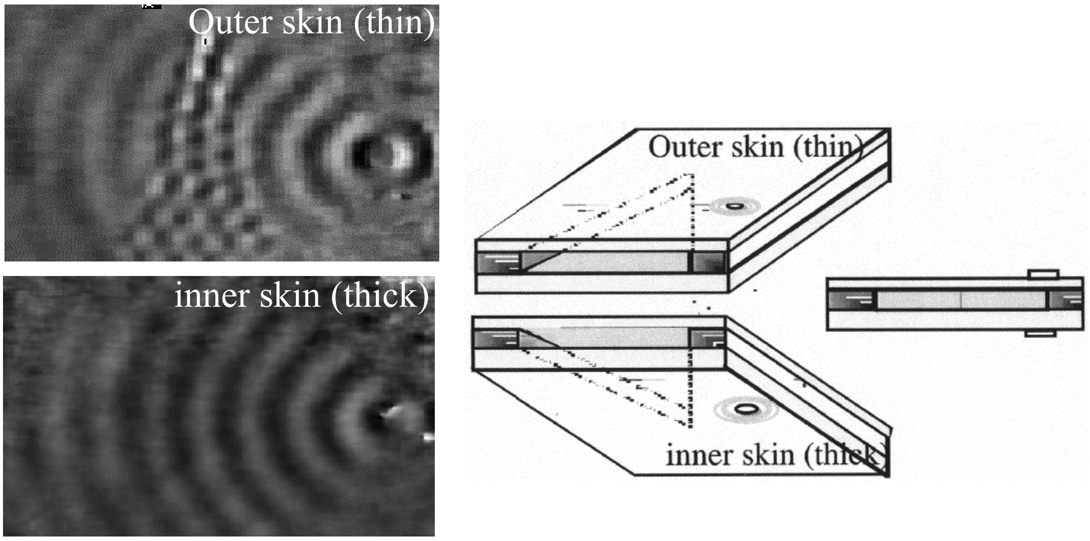
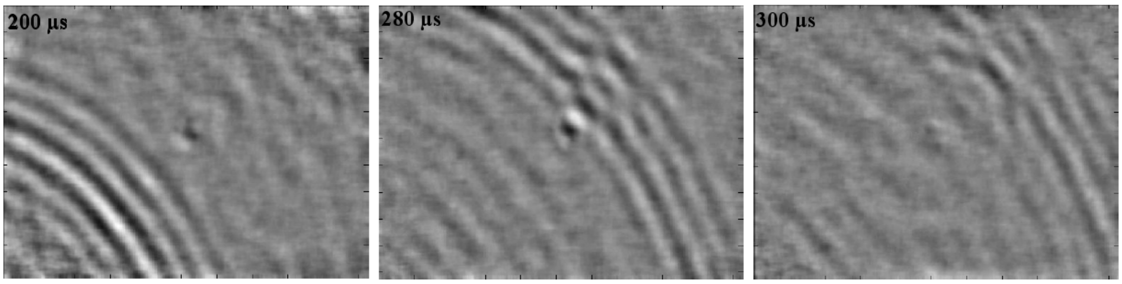


Fig. 10 – Shearographic visualization of the interaction of Lamb waves (A_0 mode, f = 20 kHz) with a defect in the core (lack of foam) in a composite sandwich of a radome, from [31].

The demonstration of the possibility to image the propagation of Lamb wave bursts has been achieved too [26,27]. We present in Figure 11 the images of the displacement recorded on the impacted sample previously monitored (see figure 9) for three different delays after the burst emission. In the first image the Lamb wave front is still upstream from the impact defect and in the second image the burst has already passed the defect. Again a 30° wide wake with a 180° phase-delay appears downstream. In the last image, a circular diffracted wave is seen around the defect. Five-period bursts have been used, with windowing, and this unavoidably induced higher frequency content for the mechanical excitation. Other modes than S_0 with different velocities and wavelengths could thus be present. Together with the fact that the bursts are repetitively emitted, this could explain why the defect already appears before the burst reaches it. Indeed small amplitude ripples can be seen in front and behind the burst.



τ = 200 µs τ = 280 µs τ = 280 µs

Fig. 11 - Shearograms of burst propagation in a delaminated C/epoxy plate (5 J impact). Transducer driven with repetitive 5-period bursts (68 kHz), taken from [27].

IMAGING LAMB WAVES INTERACTION WITH DAMAGES USING LOCK-IN THERMOGRAPHY

Principle of vibrothermography

Ultrasonic vibrothermography is a non destructive technique based on the application of a modulated mechanical stress on the tested structure, while an infrared camera is mapping the surface temperature [32]. Conversion of mechanical energy to heat is partly responsible for damping. The thermomechanical coupling includes the thermoelastic coupling effect: within the elastic range, a material experiences a reversible conversion between mechanical and thermal energy causing temperature changes. The thermoelastic term in the heat equation is proportional to the sum of principal stresses. Assuming adiabatic conditions, the corresponding temperature change is thus linear and independent of the loading frequency.

The thermomechanical coupling also includes dissipation generated by plasticity and/or viscosity. As a matter of fact, in plasticity, part of the mechanical work produced by the plastic deformation is converted to thermal energy, the other part being spent for the change of material microstructure. As a first approximation, one can express the temperature modulation versus the local stress (σ) modulation like in [33]: $T = K_{te}\sigma + K_d\sigma^2$, where K_{te} and K_d are complex-value coefficients related to thermo- elasticity and dissipation.

In polymers, where viscous dissipation is rather high, the quadratic relationship between stress and temperature variations is easily observed, at least for relatively high stress amplitude. At lower amplitude values, the thermoelastic contribution cannot be neglected anymore. Lock-in radiometry using the actuator frequency for reference was thus proposed for the analysis of polymer composites as it is very convenient to reveal the change from the thermoelastic effect to the loss angle effect [33].

Damaged regions convert energy to heat through enhanced viscoelastic dissipation, collisions and/or rubbing of internal free surfaces present in delaminations and cracks. Surface defects and internal defects appear hotter when the surface temperature is mapped, a fact that provides the basis for the use of joint mechanical excitation (either sonic or ultrasonic) and thermography as a non destructive technique.

The temperature analysis can be performed in different ways. On a differential basis, one merely compares temperature maps obtained before and after the application of mechanical stress. In [32] the delay was in the range of seconds. It can also be performed through video lock-in processing [34]. In the latter case, the high-frequency mechanical excitation is amplitude-modulated at a low frequency. The *high frequency vibrations* are used for heat generation at the defect location through the irreversible phenomena that were previously mentioned. Heat generation has a second periodicity defined by the *low frequency amplitude modulation*. The lock-in system is synchronized with this thermal wave frequency. In [34] the samples were excited with a mechanical shaker at a frequency ranging between 100 Hz and 5 kHz, while the stress amplitude was modulated from 0.03 Hz to 1.25 Hz. The applied stress ranged between 1 MPa and 47 MPa. The technique proved to be successful in detecting cracks and delaminations in a series of carbon fiber reinforced plastic (CFRP) samples; however the applied stress level was rather high. Anyway, the stressing means is not suitable for inspecting real and large structures. Another configuration tested by the same authors [35], using an ultrasound cleaner as ultrasonic source (500 W, 40 kHz), suffers from the same inconvenient.

A slightly different approach was proposed in [36,37], where a 40 kHz or 20 kHz ultrasound generator was attached to the tested component. The mentioned power ranged between 150 W and 2000 W.

Regarding the time function of the mechanical excitation, other schemes were also considered: bursts of a few hundred of milliseconds [37], and short pulses, 50-200 ms long, of high frequency ultrasound energy [39]. The reported ultrasound sources were always powerful devices, in many instances they were sonotrodes (generally designed for plastic welding) with power up to 2 kW. The use of so powerful devices may cast some doubt on the non destructive aspect of the control. The first danger is thus, in the case of polymer composite testing, to overheat the material in the contact area. The second danger is that small tolerable cracks may grow unexpectedly fast when the defect surfaces are submitted to energetic rubbing and/or "clapping".

We thus intended at ONERA to evaluate if ultrasound-thermography could be successfully applied by means of small low-energy piezoelectric transducers embedded or surface-bonded to the tested structure and generating Lamb waves (see Figure 12 the schematic presentation of the set-up used for these experiments). These transducers are currently used in acousto-ultrasonic SHM systems. This has been successfully demonstrated in the case of C/epoxy plates [28,38]. This solution presents three main advantages: i) low-power actuators (less than 1 W) can be used, inducing a low dissipation at the defect location, nevertheless detected thanks to the lock-in procedure; ii) embedding or bonding the piezoelectric patches guaranty a coupling constant in time and ascertainable by measuring the electromechanical impedance [40,41], which is essential for SHM, since it has been shown that the frequencies launched within the material depend on the coupling of the actuator with the structure [42]; iii) the use of Lamb wave permits long distance propagation with moderate attenuation, thus giving an almost uniform sensitivity to the defect detection in the full structure. The other important result of this work was the fact that the thermal contrast generated at the damage location is highly sensitive to the Lamb wave frequency.

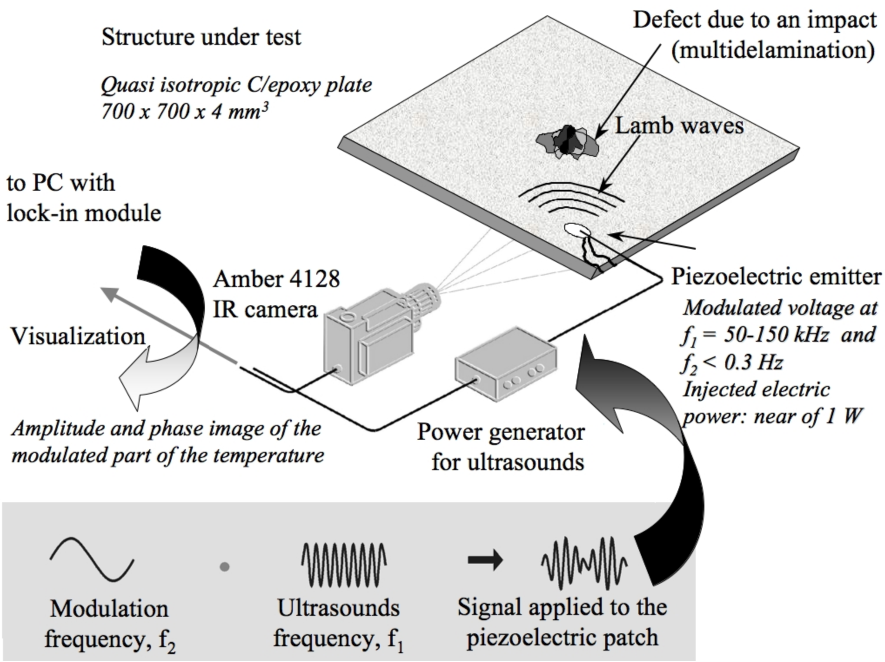


Fig. 12 - Experimental configuration used at ONERA for the visualization of Lamb waves by vibrothermography [38,43].

Since then, other investigators [44)] showed that moderate-power piezo-ceramic actuators (8 kHz, 200 W) could efficiently be used for the detection of impact delaminations in carbon fiber plates. The influence of the ultrasound frequency was also recently addressed. In [42] it was first shown that the actual vibrations produced by a single-frequency sonotrode may contain several significant harmonics. Secondly, it was observed that a 40 kHz sonotrode may produce much higher thermal contrast at a crack location than a more powerful 20 kHz sonotrode. In [45,46] the frequency choice was motivated by the avoidance of resonance modes (standing waves). As a matter of fact, if the applied frequency appears to correspond to a resonance mode of the tested structure, a thermal signal will rise only in the vicinity of displacement nodes (strain antinodes) and a defect located elsewhere will remain undetected [32]. For this reason, Dillenz and Zweschper suggested to modulate the ultrasound frequency in order to eliminate (on the average) such blind zones. A significant improvement was claimed by wobbling the frequency between 15 kHz and 25 kHz with a modulation frequency up to 25 Hz.

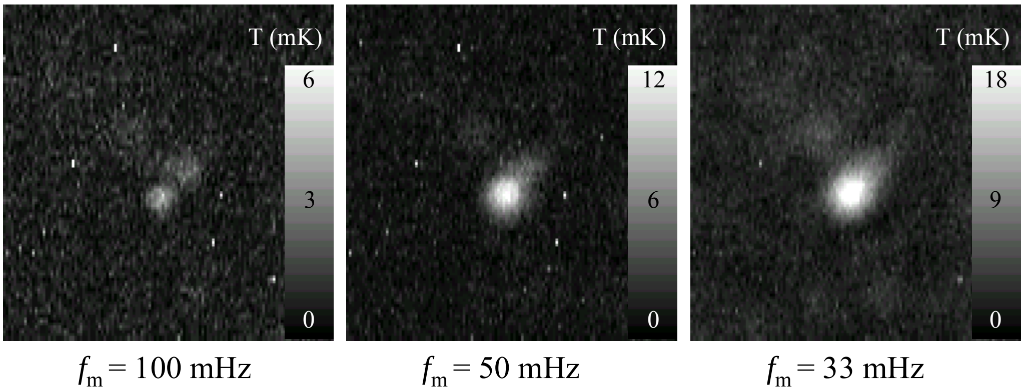
Low-energy detection of delaminations in composite panels

With the set-up presented in Figure 12 results have been obtained at ONERA using Lamb waves and very low energies. Temperature mapping was performed with an infrared focal plane array camera (Amber 4128, 128x128 pixels), operated with the maximum allowable integration time in order to reduce the noise equivalent temperature difference (NETD). In these conditions, the temporal noise for a given pixel was reduced to about 7 mK. The lock-in technique was applied to demodulate the thermal signal. The ultrasound actuator was fed with a high frequency electric modulation, between a few tens and a few hundreds of kHz and the amplitude was modulated with a sinus function or a square function at a low frequency (33 mHz to 300 mHz). By processing some 500 images, a temperature modulation amplitude image with a noise less than about 0.5-0.6 mK is obtained. Such low noise is required for the analysis of low intensity dissipation phenomena like those observed during fatigue tests [47] and those induced by ultrasound propagation and interaction with defects.

We will present some results obtained on a 700x700 mm^2 C/epoxy orthotropic plate $[0_4,45_4,90_4,-45_4]_S$, 4 mm thick. A 30 mm dia. disc-shaped actuator, 200 μm thick, was stuck near one corner of the large slab where two impacts (5 and 6 J) were performed at the same location in order to generate delaminations. The applied voltage on the piezoceramic was less than 30 V and the electric power was less than 1 W.

Influence of the low-frequency amplitude modulation

The amplitude of the Lamb waves is modulated at a low frequency (30 mHz to 300 mHz) in order to cope with the thermal wave attenuation and to detect deep defects. The modulation frequency should indeed be selected with respect to the inverse of the through-thickness diffusivity of the inspected material. In the present case the thermal frequency of the 4 mm-thick plate, $a/(\pi l^2)$, with a the through-thickness diffusivity and l the slab thickness, is about 80 to 100 mHz. The delaminations can be detected from front face (outside face which received the impact) provided the modulation frequency is low enough. Figure 13 presents the thermal amplitude images obtained for three frequencies: 100, 50 and 33 mHz. Synchronous demodulation allows detecting the defect when the modulation frequency is set to 100 mHz: a 4 mK contrast is measured, which is well above the noise level. By still reducing to 50 mHz and then to 33 mHz, the maximum contrast value increases to 13 mK and then up to 22 mK. A small double hotspot at 100 mHz can be noticed and a more blurred and wider thermal pattern for lower modulation frequencies. The defect close to the front surface is indeed made of two small delaminations as revealed by a C-scan image. By reducing the modulation frequency, one gets simultaneously a more



f_m = 100 mHz f_m = 50 mHz f_m = 33 mHz

Fig. 13 - Temperature amplitude map on the front side of the impacted area for three values of the modulation frequency (the ultrasound frequency is 112 kHz). Represented field is 12 x 12 cm2. Maximum temperature amplitude in the "hotspot" is, from left to right: 4, 13, and 22 mK. (from [38)].

blurred image of the delaminations that are close to the front surface, and a more vivid image of the deeper and actually wider delaminations. These results highlight the well known depth probing property of "thermal waves".

Influence of the Lamb wave frequency

The modulation frequency being fixed at 33 mHz in order to get a good signal to noise ratio, six different values of frequency between 50 kHz and 150 kHz were applied to the ultrasound transducer. The temperature amplitude images obtained after synchronous demodulation are presented in figure 14.

The most important observation is that the mechanical excitation frequency has a tremendous influence on the dissipation in the delaminated area. The highest contrast, i.e. 22 mK, is observed for a frequency of 112 kHz. When the actuator is excited at 148 kHz, the defect is still detectable; however the contrast has already dropped to about 8 mK.

Interestingly, with a frequency of 68 kHz, the defect can be easily detected on the shearography image (see Figure 9), whereas it is unseen on the thermal image. This figure clearly shows how dramatic is the choice of the ultrasound frequency for a safe detection by thermography. Of course, the values that we considered for the ultrasound frequency are sparse. It is thus likely that even higher contrast values can be obtained at some intermediate frequencies values. Nevertheless, it was clearly shown that dissipation can vary manifold when the ultrasound frequency is slightly changed and when different Lamb wave modes are excited.

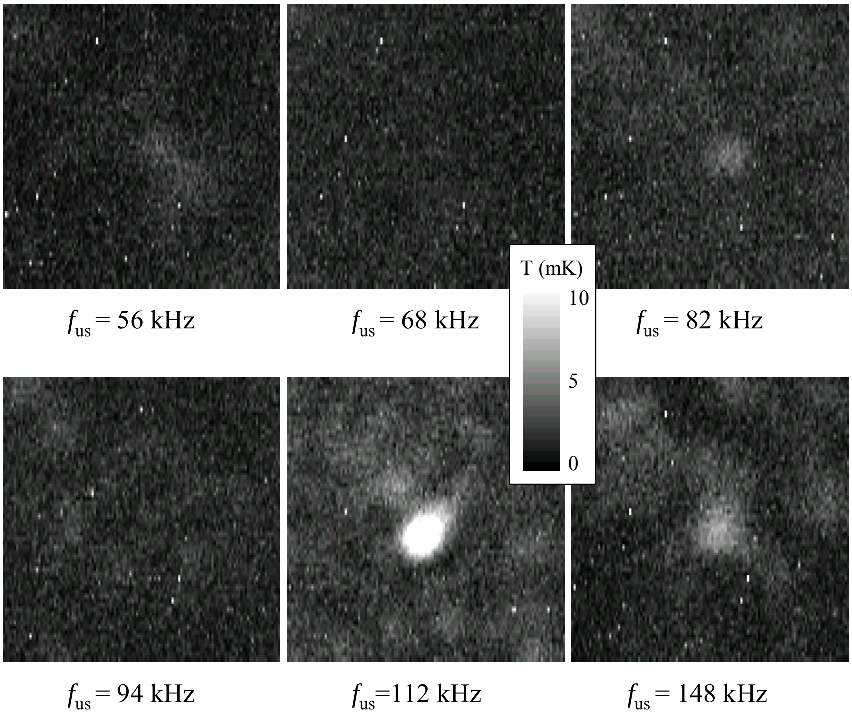


Fig. 14 - Temperature amplitude map on the front side of the impacted area for different values of the ultrasound frequency, the amplitude modulation frequency being 33 mHz. Common grey scale ranges from 0 mK to 10 mK. Image taken from [38].

From these experiments we can conclude that defects can be detected whatever their depth be, provided that dissipation is high enough and that the modulation frequency is chosen sufficiently low (thick plates need higher mechanical energy and deep defects need lower lock-in modulation frequency to be revealed). The high selectivity of the ultrasound frequency regarding the thermomechanical coupling at the defect location, has however to be taken into account. At this point, one can envision the success of ultrasound-thermography according to two ways. The first solution consists, as did previous investigators, in implementing an actuator working at a single frequency, supplying a considerably high mechanical power for compensating the most likely poor efficiency of the thermomechanical coupling in the considered tested structure. The obvious risk is then to deteriorate the tested piece. The other way requires to perform a theoretical work in order to predict, for a given structure and a given defect geometry, which kind of ultrasound wave would lead to maximum dissipation at the defect locus.

Practical applications

The experimental results just presented essentially concern delaminations in composite structures. In fact, the field of application of the technique is much wider. To illustrate this, Figure 15 presents results which concern a crack in steel part and a hidden corrosion in an aluminum alloy structure (private communication from G. Busse, IKP, Stuttgart University).

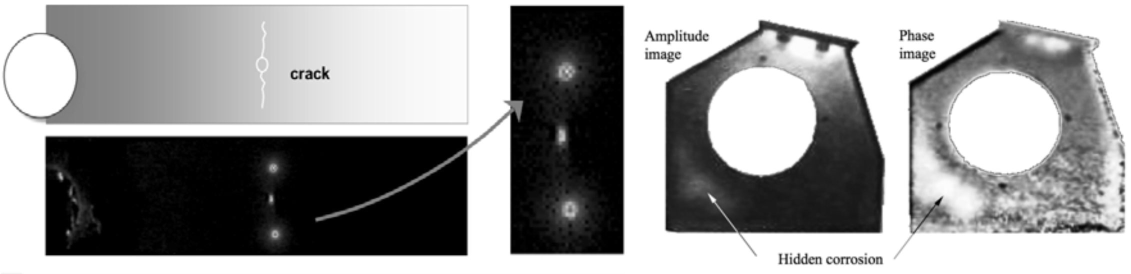


Fig. 15 – Detection by ultrasonic vibrothermography of two other generic types of defects. Left: interaction of waves diffraction with a crack in a steel part, showing the diffraction at the tips; Right: detection of hidden corrosion in an aluminum alloy aircraft part (from G. Busse from IKP, Stuttgart).

Furthermore, it must be noticed that the ultrasonic vibrothermography has already been applied to real structures presenting realistic damages. These works have been essentially performed until now by some groups using sonotrodes or PZT patches requiring high energies. The types of structures and damages until now detected in these conditions are varied. Let us mention, taken from [37,44,46]: i) delamination in skin and stringer and stringer disbonding in composite aircraft panels, ii) cracks and disbonds in metallic structures, hidden corrosions between skin and riveted stringers in aluminum structures, iii) heterogeneities in a multilayer C/C-SiC ceramic composite.

We can suppose that choosing tailored Lamb waves similar results could be obtained with low or moderate energies.

CONCLUSIONS

The concept of NDECS (Non Destructive Evaluation of Cooperative Structures) has been defined and proposed as a third possible way in between the classical NDE and SHM. The optimum NDECS is the combination of an integrated stimulation with a large-field real-time imagery performed from outside the structure. From the analysis of the present evolution of techniques in NDE and SHM fields, it has been deduced that the best NDECS solutions could be: generation of Lamb waves by structure embedded piezoelectric transducers and detection of damages by stroboscopic shearography or by lock-in infrared thermography.

To demonstrate that these solutions are applicable at a short term, experimental results have been presented which are promising.

Concerning the second NDECS method (using thermography) it has been concluded that the enhancement of the performances of the technique requires a theoretical effort to better understand the interaction phenomena. Nevertheless, we can be optimistic. Let us mention for instance the interesting results already obtained in the field of corrosion detection by Lamb waves thanks to such type of works [48,49].

Furthermore, the complementarity of the two techniques, shearography and vibrothermography, has been verified and thanks to the miniaturization of the respective set-ups (illumination laser, shearographic and thermographic camera) it would be possible to use them in parallel with the same ultrasonic stimulation. Figure 16 presents what could be the configuration of a system combining these two NDECS techniques.

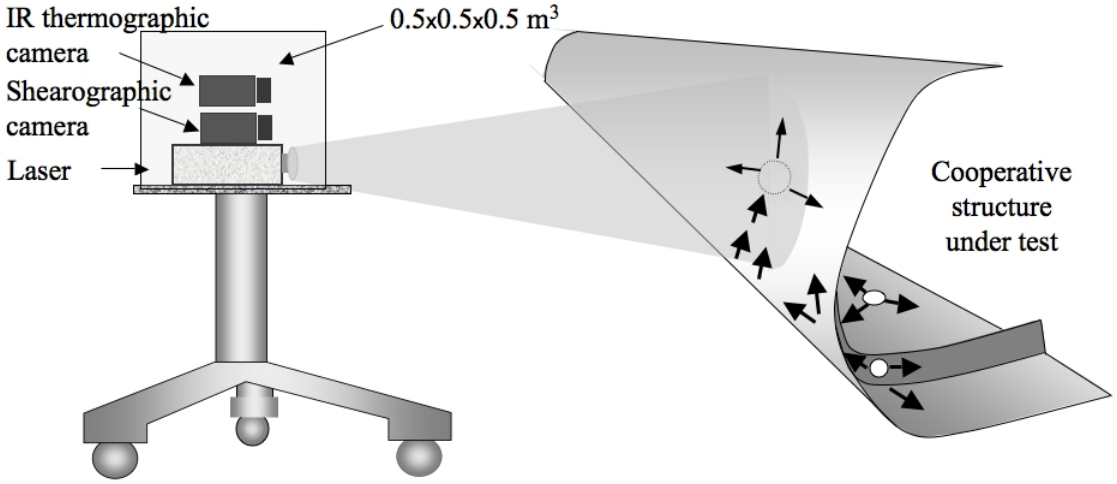


Fig. 16 – Possible configuration of a system combining the two proposed NDECS. The detection head, comprising the illumination laser, the shearographic and the infrared cameras, can be contained in a volume no larger than 0.5x0.5x0.5 m^3, making the system easily mobile.

REFERENCES

1. Rastogi P.K. Holographic Interferometry: Principles and Methods, *volume 68 of Optical Sciences. Springer-Verlag*. (1994).

2. Maldague X., Theory and Practice of infrared technology for nondestructive testing, Wiley Series in Microwave and Optical Engineering, *John Wiley and Sons Inc*. (2001).
3. Hild F., Périé J.-N. and Coret M. Mesure de champs de déplacements 2D par corrélation d'images numériques. *Technical Report 230, Ecole Normale de Cachan*, 1999.
4. Balageas D. Introduction to Structural Health Monitoring, in *Structural Health Monitoring. Eds. D. Balageas, C.-P. Fritzen and A. Güemes. ISTE Ltd.* pp. 13-43. (2006)
5. Arnould O., Hild F. and Brémond P. Thermal evaluation of the mean fatigue limit of a complex structure. Thermosense XXVII, *Proc. SPIE vol. 5783*. (2005).
6. Potet P., Bathias C. and Degrigny B. Quantitative characterization of impact damage in composite materials: a comparison of computerized vibrothermography and X-ray tomography. *Materials Evaluation*, 46 (8), pp. 1050-1054. (1988).
7. Tenek L.H., Henneke E.G. II and Gunzburger M.D. Flaw dynamics and vibro-thermography thermoelastic NDE of advanced composite materials, in *Thermosense XIII, SPIE Proc. Vol. 1467*, pp. 252-263. (1991).
8. Vavilov V., Infrared non-destructive testing of bonded structures: aspects of theory and practice, *British Journal of Non-Destructive Testing*, July, pp. 175-183. (1980).
9. Balageas D.L., Déom A.A. and Boscher D.M. Characterization and nondestructive testing of carbon-epoxy composites by a pulsed photothermal method, *Materials Evaluation*, 45 (4), pp. 461-465. (1987).
10. Riegert G., Zweschper Th. and Busse G. Lock-in thermography with eddy-current excitation, *QIRT (Quantitative InfraRed Thermography) Journal*, vol. 1 (1), pp. 21-31. (2004).
11. Balageas D.L., Levesque P., Nacitas M., Krapez J.-C., Gardette G. and Lemistre. Microwaves holography revealed by photothermal films and lock-in IR thermography: application to electromagnetic materials NDE. NDE of aging infrastructure and manufacturing. *Proc. SPIE vol. 2944*, pp. 55-66. Also: ONERA TP 1996-149. (1996).
12. Pinassaud J., Joubert P.Y, Decitre J.M. and Lemistre M. Quantitative Magneto-Optic Imager for Non-destructive Evaluation. In *Proc.10th SPIE International Symposium on NDE for Health Monitoring and Diagnostics,* San Diego, March 6-11, (2005).
13. Ikegami R. Structural Health Monitoring: Assessment of Aircraft Customer Needs. Structural Health Monitoring 2000, *Proc. of the Second International Workshop on Structural Health Monitoring*, Technomic Publishing Co, Inc, Lancaster – Basel, p. 12-23. (1999).
14. Goggin P., Huang J., White E., Haugse E. Challenge for SHM transition to future aerospace systems. In *Structural Health Monitoring 2003, From Diagnostics & Prognostics to Structural Health Management. Proc. of the 4th Intern. Workshop on Structural Health Monitoring*, DEStech Publications, Inc, Lancaster, PA, USA, p. 30-41. (2003).
15. Derriso M.M., Pratt D.M., Homan D.B., Schroeder J.B., Bortner R.A. Integrated Vehicle Health Management: the key to future aerospace systems. In *Structural Health Monitoring 2003, From Diagnostics & Prognostics to Structural Health Management, Proc. of the 4th Intern. Workshop on Structural Health Monitoring*, DEStech Publications Inc, Lancaster, PA, USA, p. 3-11. (2003).
16. Walsh S.M.. Practical issues in the development and deployme,t of intelligent systems and structures. *Structural Health Monitoring 2000, Oroc. Of the Second Intern. Workshop on Structural Health Monitoring*, Stanford, CA. September 8-10, 1999 . Ed. Fu-Kuo Chang, Technomic Publishing Co., Lancaster-Basel, pp. 612-621. (1999).
17. Leendertz J. and Butters J. An image shearing speckle pattern interferometer for measuring bending moments, *J. Phys. E: Sci. Instrum*., 6, 1107-1110. (1973).

18. Hung Y.Y. A speckle-shearing interferometer : a tool for measuring derivatives of surface displacements, *Optics Communications*, 11 (2), pp. 132-135. (1974).
19. Hung Y.Y. Shearography: a novel and practical approach for non-destructive inspection. *Journal of Nondestructive Evaluation*, 8 (2), pp. 55-67. (1989).
20. Clarady, J.F. and Summers. Electronic holography and shearography NDE for inspection of modern materials and structures, *Review of Progress in QNDE*, 12, pp. 381-386. (1993).
21. Lamarque T. Caractérisation de délaminages par interférométrie de speckle à cisaillement avec solicitation thermique ou mécanique. *Note Technique ONERA*, NT 1998-11. (1998).
22. Paoletti, D., Schirripa Spagnolo, G., Zanetta, P., Facchini, M. and Albrecht, D. Manipulation of speckle fringes for non destructive testing of defects in composites. *Optics & Laser Technology*, 26 (2), pp. 99-104. (1994).
23. Hariharan P. and Oreb B.. Stroboscopic holographic interferometry: Application of digital. *Optics Communications*, 59, (2), 83 86, August (1986).
24. Bard B.A., Gordon, G.A. and Wu, S. Laser modulated phase-stepping digital shearography for quantitative full-field imaging of ultrasonic waves. *J. of Acoust. Soc. Am.,* 103, p. 3327. (1998).
25. Krapez, J.-C., Taillade F., Lamarque T. and Balageas, D. Shearography : a tool for imaging Lamb waves in composites and their interaction with delaminations, in *Review of Progress in QNDE, vol. 18a*, pp. 905-912. (1999).
26. Taillade F., Krapez J.-C., Lepoutre F. and Balageas D. Shearographic visualization of lamb waves in carbon epoxy plates: interaction with delaminations. *The European Physical Journal-Applied Physics,* AP 9, pp. 69-73. (2000).
27. Taillade F., Krapez J.-C., Lamarque T., Balageas D. and Lepoutre F. Visualisation par shearographie des ondes de Lamb dans les matériaux composites – Interaction avec les délaminages. In *Instrumentation, Interdisciplinarité et Innovation*. Eds. D. Placko and E. Santander. Hermes, Paris, PP. 263-272 ; (1999).Also: ONERA TP 1999-16.
28. N. Rastogi P.K.. Measurement of in-plane strains using electronic speckle and electronic speckle-shearing pattern interferometry, *Journal of Modern Optics*, 43, (8), pp. 1577-1581. (1996).
29. Moulin E., Assaad J., Delebarre C., Kaczmarek H. and Balageas D., Study of a piezoelectric transducer embedded in composite plate : application to Lamb waves generation., *Journal Applied Physics*, Vol. 82, n°5, pp. 2049-2055. (1997).
30. Taillade F. Association de la shearographie et des ondes de Lamb pour la détection rapide et quantitative des délaminages (Shearography and Lamb waves combined for fast detection and characterization of delaminations), *PhD Thesis, CNAM*, Paris. (2000). - also: ONERA Technical Note: ONERA NT 2001-3 (2001).
31. Devillers D., Taillade F., Osmont D., Krapez J.-C., Lemistre,M. and Lepoutre F.. Shearographic imaging of the interaction of ultrasonic waves and defects in plates. In *5th Annual International Symposium on Nondestructive Evaluation and Health Monitoring of Aging Infrastructure, volume 3993 of SPIE Proc., pp. 142-149. SPIE*, Bellingam, (2000).
32. Mignona R.B., Green R.E., Duke J., Henneke E.G., Reifsnider K.L. Thermographic investigation of high-power ultrasonic heating in materials. *Ultrasonics*, vol. 7, pp. 159-163. (1981).
33. Busse G., Bauer M., Rippel W., Wu D. Lockin vibrothermal inspection of polymer composites. *Proc. of QIRT 92*, Editions Européennes Thermique et Industrie, Paris, pp. 154-159. (1992).
34. Rantala J., Wu D., Busse G. Amplitude modulated lockin vibrothermography for NDE of polymers and composites. *Res. Nondestr. Eval.* , vol.7, pp. 215-218. (1996).
35. Rantala J., Wu D., Busse G. NDT of polymer materials using lock-in thermography with water-coupled ultrasonic excitation. *NDT&E Int.,* vol. 31, n°1, pp. 43-49. (1998).

36. Rantala J., Wu D, Salerno A., Busse G. Lock-in thermography with mechanical loss-angle heating at ultrasonic frequencies. *Proc. Quantitative Infrared Thermography Conference, QIRT 96,* Eurotherm series 50, Edizioni ETS, Pisa, pp. 389-393. (1997).
37. Busse G., Dillenz A., Zweschper T. Defect-selective imaging of aerospace structures with eleastic-wave-activated thermography. *Thermosense XXIII SPIE Conf., SPIE ed., vol. 4360*, pp. 580-586. (2001).
38. Krapez J.-C., Taillade F. and Balageas D. Ultrasound-lock-in thermography NDE of composite plates with low power actuators. Exprimental investigation of the influence of the Lambwave frequency. *QIRT Journal*, vol. 2, N°2, pp. 191-206. (2005).
39. Favro L.D., Han X., Zhong O.., Sun G., Sui H., Thomas, R.L. Infrared imaging of defects heated by a sonic pulse. *Rev. Sc. Instrum.,* vol. 71, n°6, pp. 2418-2421. (2000).
40. Giurgiutiu V., Zagrai A., and Bao J.J. Piezoelectric wafer embedded active sensor for aging aircraft structural health monitoring, *SHM*, vol. 1, n° 1, pp. 41-62. (2002).
41. Pacou D., Pernice M., Dupont M., Osmont D. Study of the interaction between bonded piezo-electric devices and plates. *Proc. of the First European Workshop on Structural Health Monitoring,* ed. D.L. Balageas, DEStech Publ. Inc., Lancaster (PA), pp. 406-413. (2002).
42. Han X. Frequency dependence of the thermosonic effect. *Rev. Sci. Instrum.,* vol. 74, n°7, pp. 414-416. (2003).
43. Krapez J.-C., Taillade F., Balageas D. Vibrothermographie par ondes de Lamb : vers une nouvelle méthode de CND ?. Journée “Thermographie quantitative” de la Soc. Fr. des Thermiciens, Châtillon (France), 31 mars 1999 (unpublished)
44. Dillenz A., Zweschper T., Busse G. Burst phase-angle thermography with elastic waves. Thermosense XXIV, *SPIE Proc., vol. 4710*, pp. 572-577. (2002).
45. Dillenz A., Zweschper T., Riegert G., Busse G. Progress in phase angle thermography. *Review of Sci. Instrum.* Vol. 74, n° 7, pp. 417-419. (2003).
46. Zweschper T., Riegert G., Dillenz A., Busse G. Frequency modulated elastic wave thermography. *Thermosense XXV, SPIE Proc. , vol. 5073*, pp. 386-391. (2003).
47. Krapez J.-C., Pacou D. Thermography detection of damage initiation during fatigue tests. Thermosense XXIV SPIE Conf., X.P. Maldague, A.E. Rozlosnik, Eds., *Proc. of SPIE, vol. 4710*, p. 435-449. (2002).
48. Terrien N., Royer D., Lepoutre F. and Déom A. Optimization of hidden corrosion in aircraft structures using Lamb waves: numerical predictions and experimental results. To be published in *Review of Progress in QNDE,* Eds. D.O. Thompson and D.E. Chimenti, vol. 26. (2007).
49. Terrien N., Royer D., Lepoutre F. and Osmont D. Optimization of corrosion monitoring using Lamb waves, in *Review of Progress in QNDE,* Eds. D.O. Thompson and D.E. Chimenti, vol. 24 A, pp. 134-141. (2005).

Generic references

Proceedings of NDE-specialized conferences

A. Review of Progress on Quantitative Non Destructive Evaluation, Proceedings of the Conference on Quantitative Non Destructive Evaluation (QNDE), published each year since 1982, the year following the conference year, by Kluwer Academic/Plenum Publishing, New-York.

Proceedings of SHM-specialized conferences (Acronym - full title – years - publisher)

B. IWSHM: International Workshops on Structural Health Monitoring, 1997, 1999 – Technomic Publishing; 2001 – CRC Press, New-York; 2003 and 2005 - DES*tech* Publication Inc, Lancaster, PA, USA.

C. EWSHM: European Workshops on Structural Health Monitoring, 2002, 2004, 2006. Published by DES*tech* Publication Inc, Lancaster, PA, USA.

D. APWSHM - Asia-Pacific Workshops on Structural Health Monitoring - 2006.

E. DAMAS - Conf. on Damage Assessment of Structures - 1997, 1999, 2001, 2003, 2005 - various publishers.

F. HMSBS SPIE: Health Monitoring of Structural and Biological Systems proceedings- SPIE Proc. vol. 4335 (2001), 4702 (2002), 5047 (2003), 5394 (2004), 6177 (2006) - Published by SPIE.