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Damage detection in composites by vibrothermography and local resonances

Philippe Demy[1,a], Jean-Claude Golinval[1] and Daniel Simon[2]

[1] Département d'aérospatiale et mécanique, Université de Liège, LTAS – Vibrations et identification des structures, Chemin des Chevreuils 1, 4000 Liège 1, Belgique
[2] V2i, Pôle d'Ingénierie des Matériaux de Wallonie, Boulevard de Colonster, 4000 Liège, Belgique

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Abstract – Vibrothermography is an active thermographic technique able to detect singularities like delamination in composite materials. Carbon fibre laminates are increasingly used, especially in aviation industry where defect detection is directly related to safety. Physical causes of the internal heating mechanism linked to defect interaction with the elastic waves may be friction, viscoelastic hysteresis or plasticity. The method can efficiently detect flaws on complex geometries and only requires that both internal faces or edges are free to vibrate. The purpose of this work is to determine the relation between the observed heating right above a delamination by an IR camera and the frequency of a sinusoidal excitation between 8 and 27 kHz. The results clearly show specific heating peaks at certain frequencies. The comparison with local resonance frequencies of the delamination computed by simplified FEM shows similarities with the appearance of heating peaks. An experimental study having as goal to exploit the presence of those peaks and thus to increase the sensitivity of the method shows the interest for a high sweep sinusoidal excitation of the chirp type. The final objective of this research is to set up a serviceable short and reliable vibrothermographic test for non-destructive testing of composite materials.

Key words: vibrothermography / thermosonic / delamination / composite

1 Introduction

Vibrothermography (abbreviated VT) is an active non destructive technique able to detect singularities like delamination, whether the defect internal faces are in contact or not. Under sonic or ultrasonic mechanical vibrations, a delamination may behave like an internal heat source due to friction between the rubbing faces and/or viscoelastic hysteresis heating in the defect area. Local plastic deformation losses are discarded provided the stress level is kept well within the point of yield [1–3]. Despite numerous finite element simulations and theoretical explanations, there is still a lack of understanding concerning the physics governing the heat generation mechanism and no definitive experimental validation of either theory has been presented and accepted to date to explain the source or sources of heat generation in vibrothermography [4–11].

The present article first focuses on the research of links or evidences concerning a dominant heat generation mechanism in polymer composite related to possible "local resonances" phenomenon produced on one side or the other of the delamination [12]; that is to say the resonances of one or the other laminated sub-plate created and delimited by the delamination. High stress concentrations due to the dynamic amplification at local resonance may be correlated with the presence of corresponding heating peaks observed on the surface right above the defect by an infrared camera. For this purpose, a finite element modal analysis of the delamination has been proposed and compared with the heating rate versus frequency curve established by a series of consecutive short sine tests with a 200 Hz frequency interval. According to the comparison, vibration damping related to

Nomenclature

CFRP	Carbon Fiber Reinforced Plastic
DP	Data Physics
FEM	Finite Element Model
FRF	Frequency Response Function
IR	Infrared
NETD	Noise Equivalent Temperature Difference
VT	Vibrothermography

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[a] Corresponding author: `pdemy@doct.ulg.ac.be`

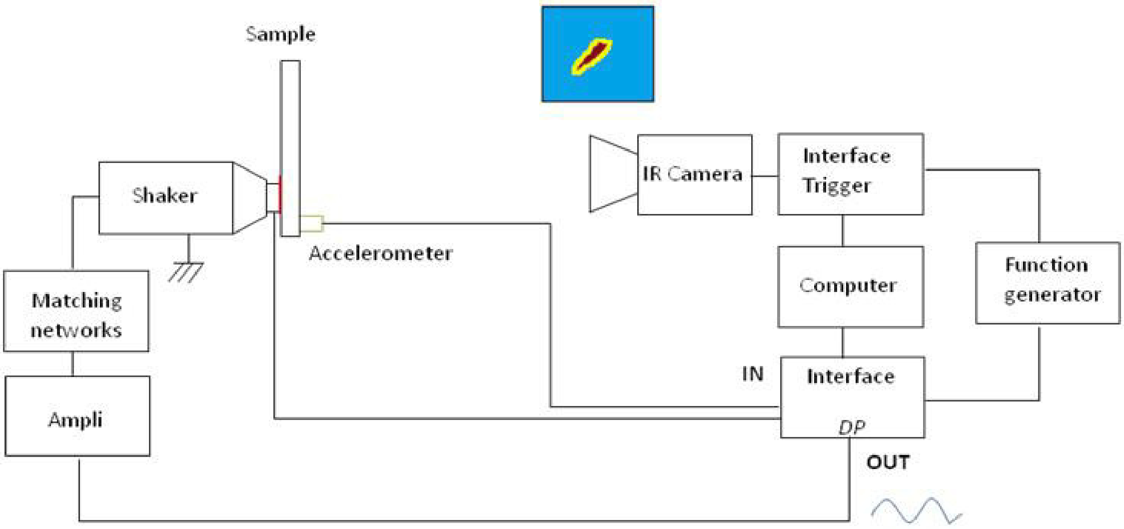

Fig. 1. Test setup.

viscoelatistic effects is expected to play a significant role, especially when matching or close to a local resonance frequency.

Secondly, linear and logarithmic sine sweep and chirp testing results will be presented and discussed exploiting the presence of the specific peaks revealed in the spectrum.

Finally, it should be noted that this paper presents an alternative method to the common usage by the nature of the contact between the vibration transducer and the specimen. Indeed, vibrothermographic devices usually have a pneumatically-driven coupling system pressing the transducer against the sample. The hammering of the surface generates non linearities induced by the acoustic chaos. It follows that the coupling pressure has a strong influence on the detection efficiency and poor coupling creates unwanted heat in the vicinity of the contact. Moreover, the risk of damaging the composite is always present [13–16]. For the purpose of this study, reproducible pure sine testing is performed by the way of a rigid tip-specimen coupling obtained by the gluing of the specimen directly on the vibration transducer head (larger plates may rest on a vibration isolation material like Teflon pieces).

2 Experimental setup

The measurement set-up used for this study is detailed in Figure 1. A piezoelectric shaker (Wilcoxon model F7) is driven by a Data Physics (DP) interface. A thermal camera (50 mK NEDT, 8−14 μm range) is triggered at the DP start-up signal by a function generator. The excitation signal is monitored via a force sensor located in the shaker head. An additional vibration sensor or a laser vibrometer may be used to provide FRF's (Frequency response Function).

The CFRP (Carbon Fiber Reinforced Plastic) sample is an eight plies symmetric laminated plate $[90/0_3]_s$, which contains a 25 × 25 mm Teflon® insert between the third and the fourth ply. The sample plate has been bounded to the shaker head with high performance cyanoacrylate glue. No other contact than this rigid coupling is produced on the plate. Note that for a short time testing, a little Kapton® tape may be placed on the plate at the location of the coupling, the shaker head being bounded to the tape.

This situation is different than usual VT setup which consists in pressing the excitation device by a controlled (or not) static force against the plate, causing some beneficial acoustic chaos but inducing major problems like non reproducibility or fretting of surfaces [13–15].

3 Laminated plate theory and finite element models

3.1 Local resonance model hypothesis

For sake of simplicity, delamination may be modelled as two separated small sub-plates, one on either side of the detachment, both free to resonate with their own dynamics but clamped together along the boundary, disregarding the remainder of the panel (Fig. 2). This idea has been first proposed by Henneke in 1990 [12]. Local resonances associated to the delamination may then be determined using the laminated plates theory and Hamilton's principle [17, 18].

The boundary conditions in the delamination region would thus actually be "kinematical continuity" along the edges.

Although any forced response to an excitation signal may lead to internal heating caused by rubbing of the sub-plates, it can be expected higher heating rates at local resonances for which higher amplitude, stress and rubbing

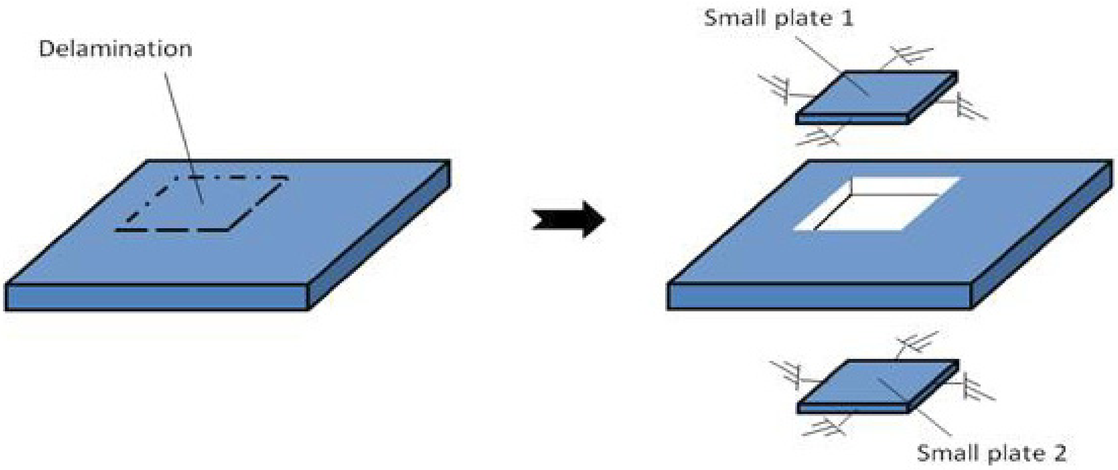

Fig. 2. Local resonance model.

Table 1. Material properties.

CFRP orthotropic ply	Index 1: fiber axis,	2,3: transverse axes
Young modulus	$E_1 = 140$ GPa,	$E_2 = E_3 = 9.2$ GPa
Poisson ratio	$\upsilon_{12} = \upsilon_{13} = 0.335$	$\upsilon_{23} = 0.38$
Shear modulus	$G_{12} = G_{13} = 4.4$ GPa	$G_{23} = 3.3$ GPa
Mass density	$\rho = 1580$ kg.m^{-3}	
Ply thickness	$t = 0.268$ mm	

Table 2. Local resonances frequencies summary [kHz].

	3 plies sub-plate				5 plies sub-plate	
	M(1,1)	M(1,2)	M(2,1)	M(2,2)	M(1,1)	M(1,2)
FEM 1	9.2	16.2	20.5	25.2	15.5	24.8
FEM 2	8.5	14.5	18.4	23.5	13.2	23.0
Mean value	8.9	15.4	19.5	24.4	14.4	23.9

are involved in the phenomenon. Otherwise, the proximity of both sub-plates surely induces contact non linearities which are difficult to take into account.

3.2 Finite element models

In this section, modal analysis results obtained with the finite element software SAMCEF are first shown for a clamped laminated rectangular plate (FEM1). The square size of the delamination is 25 mm and the material properties of the tested composite, i.e. HexPly_6376C_HTS(12K)_10_35% are reported in Table 1.

The mode-shapes obtained for a three plies $[90/0_2]$ and a five plies $[90/0_4]$ CFRP laminated sub-plate are presented in Figure 3 for a frequency range up to 27 kHz.

This model is clearly expected to be stiffer than in reality resulting in overestimated resonance frequencies. A second model (FEM2) consists to model the sample plate in free-free boundary conditions and to include only one of the sub-plate in the middle. Composite shells have been used in this case. (The results extracted from a lot of numerical modes containing also the complete sample plate resonances are provided in Fig. 4).

Mean values will be used for comparison with experimental data and are summarized in Table 2. $M(x, y)$ defines the frequency of the associated mode shape, with x along the fibre axis and y along the in-plane transverse axis.

4 Experimental results

4.1 Heating rate peaks versus frequency

The comparison between modelling and experimental results is now investigated. The average temperature in a zone right above the defect area has been recorded during a four seconds time period. The heating rate has been determined by the root mean squares lines obtained at each sinusoidal testing by step of 0.2 kHz in the range 8 to 27 kHz. The results are given in Figure 5 and are correlated with computed values from the local resonance model represented by dashed vertical lines.

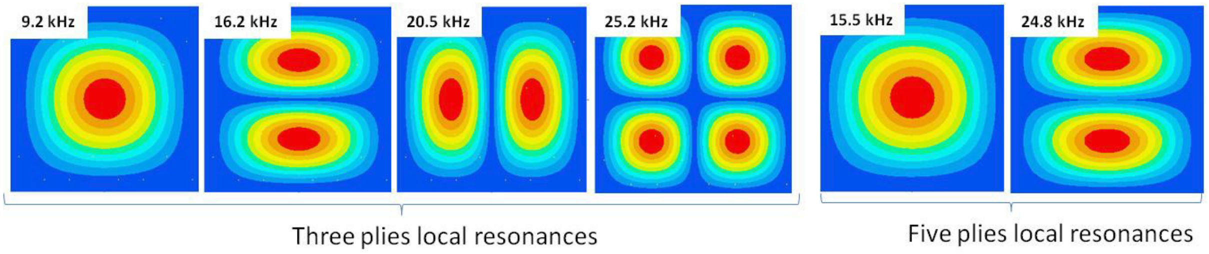

Fig. 3. Three & five plies local resonances (FEM 1).

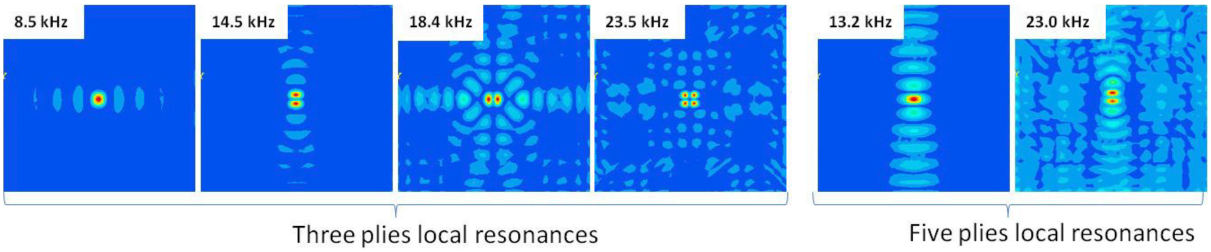

Fig. 4. Three & five plies local resonances (FEM 2).

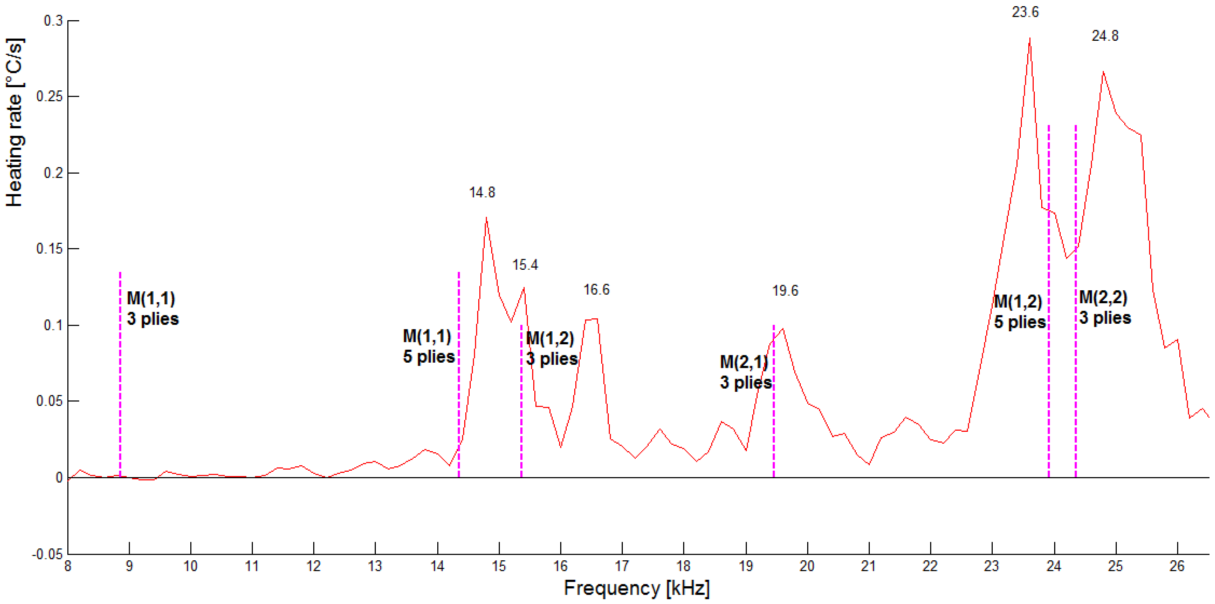

Fig. 5. Heating rate vs. frequency.

The curve reveals the presence of main heating peaks at 14.8, 15.4, 16.6, 19.6, 23.6 and 24.8 kHz.

Five of them are very close to computed local resonances either from the three plies or the five plies laminated sub-plate. The peak at 16.6 kHz is still under investigation but could correspond to an anti-resonance of a sub-plate or another phenomenon happening on the sample plate.

It can be observed that the computed resonance frequency at 8.9 kHz does not correlate with an observed heating rate peak. It may be due to the fact that the shaker output response decreases significantly below 14 kHz (using constant five volts peak input voltage).

4.2 Sine sweep testing

It has been previously shown by step-sine testing that some frequency intervals exist in which the heating caused by delamination is higher. Based upon this observation, it seems interesting to exploit the presence of those heating peaks in order to develop a reliable and quick vibrothermographic test. To this purpose, a linear sine sweep

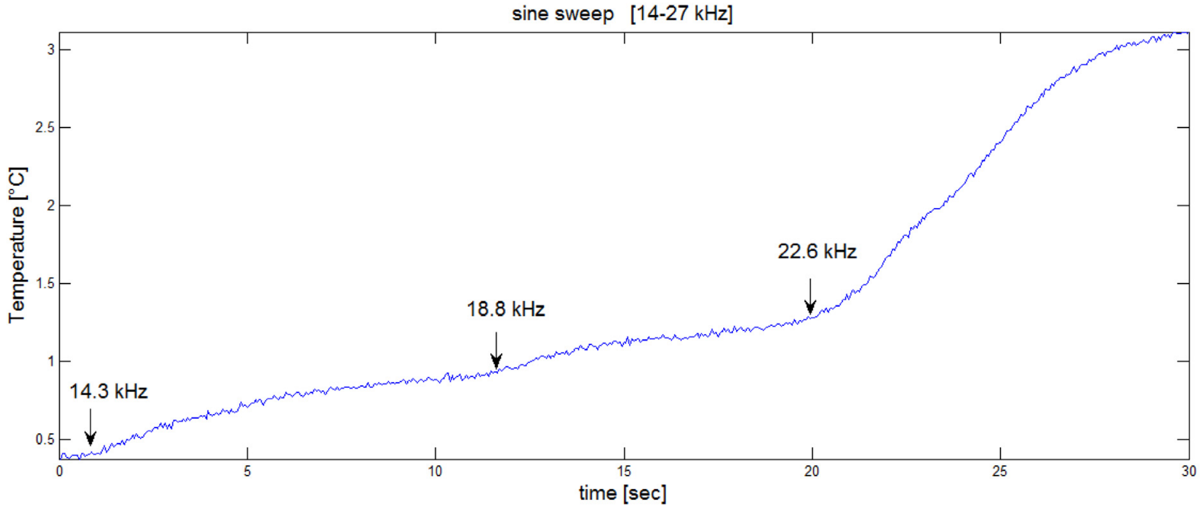

Fig. 6. Temperature increase during linear sine sweep testing.

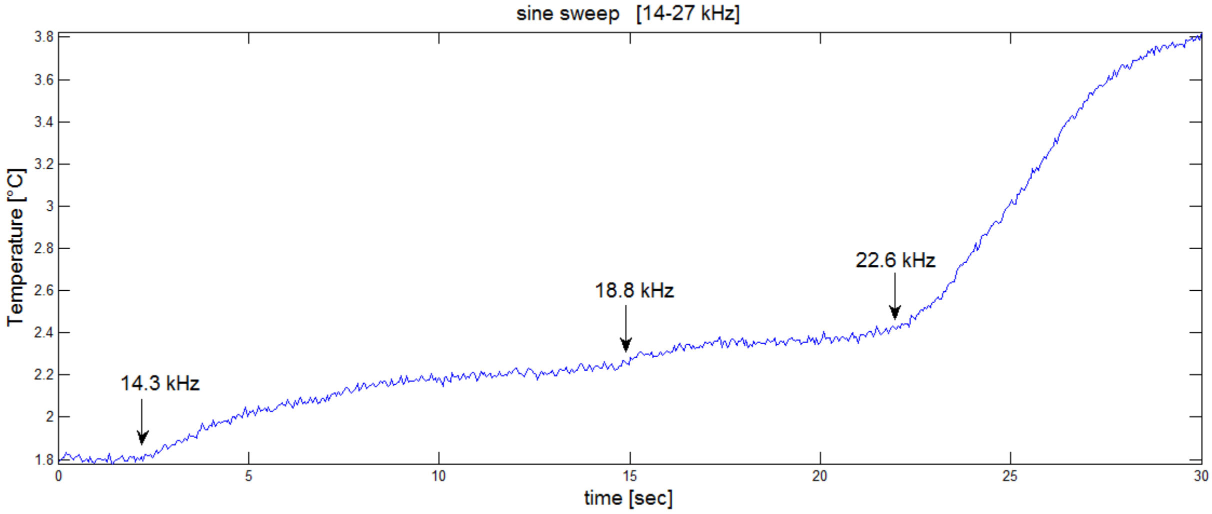

Fig. 7. Temperature increase during logarithmic sine sweep testing.

testing has been first produced. The sweep has been performed between 14 and 27 kHz at a sweep rate of 433 Hz.s^{-1} during thirty seconds. Due to thermal inertia effects, the temperature is continuously rising during the test as can be seen in Figure 6.

Three bumps are clearly visible corresponding to the lower bound of the three well separated heating intervals identified in Figure 5. The total temperature increase by accumulated heat trapped in the defect area by the composite material is about 2.5 °C.

A logarithmic sweep test has shown the same characteristics with more marked bumps and a total temperature increase of 2 °C (Fig. 7).

4.3 Chirp excitation

The chirp is short duration signal consisting in a band-controlled fixed amplitude sine wave which has the form shown in Figure 8.

A periodic chirp input signal of forty milliseconds has been tested in the 14–27 kHz range. The temperature rise for a three seconds testing is presented in Figure 9.

The temperature increase in the defect zone is practically linear with a mean slope of about 0.084 °C.s^{-1}. This value is slightly higher than the mean heating rates obtained for sine sweep testing (evaluated to 0.077 °C.s^{-1} in the same range of frequencies).

This characteristic constitutes an advantage for the development of a quick vibrothermographic test procedure.

5 Conclusions

A local resonance model has been presented for the case of a rectangular delamination in a CFRP composite material. Two finite element models were proposed in order to determine the possible frequency resonances associated to the defect.

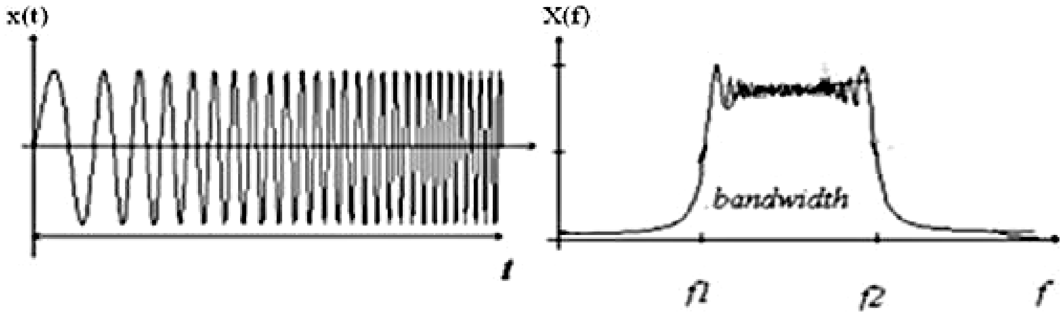

Fig. 8. Time history and spectrum of a chirp signal.

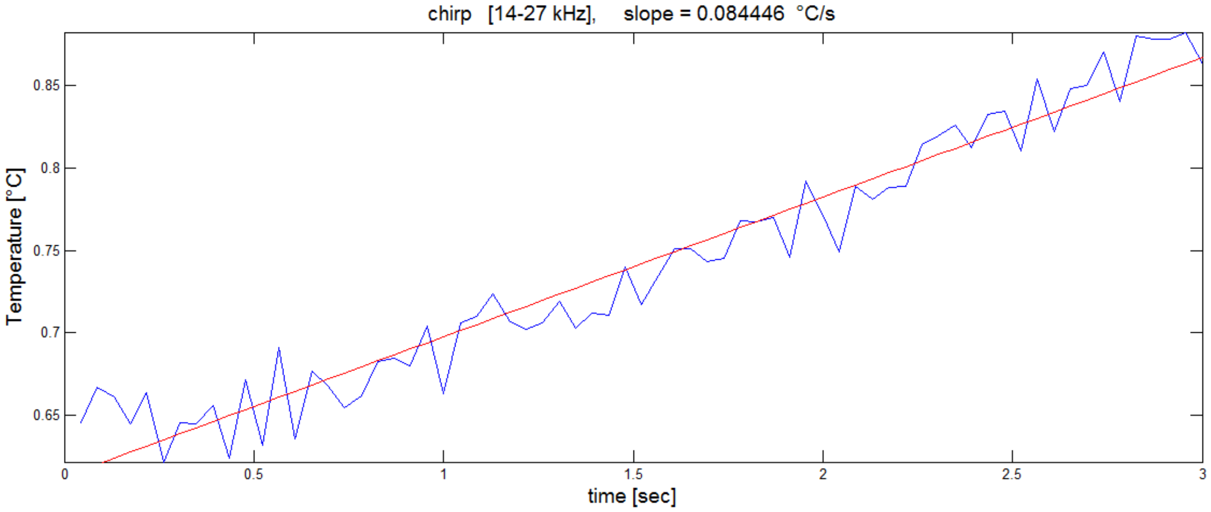

Fig. 9. Temperature increase during chirp test (3 s).

Most of the computed resonance frequencies are located very close to the highest heating peaks observed by the IR camera during step-sine testing of the sample. Those similarities are likely an indication of a significant role played by the viscoelastic hysteresis effects as heating source mechanism which should be taken into account in polymer composite numerical simulations, especially at frequencies close to local resonance frequencies of the delamination. Further investigations are in progress to attempt to bring out the local resonance phenomenon by the way of the experimental modal analysis. Also, collected data on both side of the specimen by vibrothermography could help in the evaluation of the relative roles played by the friction and hysteresis mechanisms.

Moreover, linear and logarithmic sine sweep testing performed on the sample have revealed the possibility to obtain a continuous heating during the sweep. Some bumps in the temperature curves may be associated to the presence of expected related resonance frequencies.

Excitation chirp signals have shown a better potential to exploit the presence of temperature peaks, which is very interesting when their associated frequencies are unknown.

Based upon the fact that in a practical case, the local resonances and associated viscoelastic hysteresis heating effects would depend upon the local geometry and depth of the damage region, consecutive short chirp tests covering adjacent frequency ranges should be considered advantageously for reliable and enhanced detection of delaminations by vibrothermography.

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