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Rayleigh Modes Generated by Laser-Ultrasonics at the Film-Substrate Interface for the Study of Adhesion

M. Robin, M. Chrifi Alaoui, F. Jenot, M. Ouafitouh, M. Duquennoy

Univ. Polytechnique Hauts-de-France, Univ. Lille, CNRS, UMR 8520 - IEMN - Institut d'Electronique de Microélectronique et de Nanotechnologie, F-59313 Valenciennes, France
Meriem.chrifialaoui@uphf.fr



Adhesion testing of film-on-substrate structures by surface acoustic waves is a complex issue. Indeed, the fluctuations of some parameters like the film thickness can lead to misinterpretation of the experimental results. Additionally, in laser-ultrasonics, the positions of the generation and detection sources influence the excited and detected parts of the Rayleigh modes as well as the behavior of these surface acoustic waves when the adhesion decreases. While most studies published are focused on the generation of these waves on the film surface, we use an excitation at the interface between the film and the substrate in order to study the adhesion of the structure. To that end, a transparent PVC film with a quasi-constant thickness is placed in direct contact with an aluminum substrate and the laser pulses used are focused through the film at the interface. Finite element simulations are first presented to study the influence of the source position for several adhesion degrees then experimental results complete this work.

1 Introduction

Film-on-substrate structures are widely used in several industrial fields, especially in microelectronics. The adhesion of the film to the substrate is directly linked to the lifetime of this kind of samples. It is therefore relevant to develop a non-destructive testing method to study the adhesion in these structures.

To that end, surface and guided acoustic waves are interesting. Indeed, the dispersive behavior of this kind of waves propagating in layered media is directly influenced by the contact conditions between the layers. In addition, these waves propagate over relatively long distances and allow to test quickly a significant part of the sample. The acoustic waves considered in this study are the Rayleigh modes. These are surface acoustic waves propagating in a structure composed by one or several layers deposited on a substrate considered as semi-infinite compared to the acoustic wavelength.

To generate and detect these waves, the laser-ultrasonics method has been chosen. It offers many advantages as a non-contact generation and detection in a large frequency bandwidth. These characteristics are useful for testing film-on-substrate structures.

Adhesion testing of layered structures by surface or guided acoustic waves generated and detected by laser sources is studied since several years [1-10]. One of the most important difficulties in this type of study is that the fluctuations of the layer thickness can influence the dispersion of the waves in a similar way to the adhesion, which can therefore distort the interpretation of the experimental results.

In order to avoid this problem, a PVC film with a quasi-constant thickness is placed in direct contact with an aluminum substrate. In addition, this film is transparent to the laser wavelength (532 nm) used to generate the acoustic waves. This allow us to focus the laser pulse through the film, directly on the substrate surface. In this way, the acoustic source is placed at the interface between the film and the substrate.

While most of the existing studies generate and detect the acoustic waves at the surface of the sample, we have shown that the behavior of the dispersion curves of the Rayleigh modes when the adhesion decreases is changed by placing the acoustic source at the film-substrate interface [10]. When the laser source is focused on the film surface, the Rayleigh modes tend towards the Lamb modes propagating in the film for bad adhesion cases [10 - 11]. For a source placed at the substrate surface, at the interface between the film and the

substrate, the Rayleigh modes become non-dispersive and tend towards the Rayleigh wave in the substrate when the contact conditions are weak [10]. However, this study ([10]) considers only two generation and detection configurations: at the film surface and at the interface on the substrate side.

First, we studied the influence of the positions of the source and of the detection with several adhesion degrees for four different configurations through Finite Element simulations.

Then, a study of the PVC film adhesion to the aluminum substrate depending on the location and the size of a contact surface is performed experimentally through the dispersion of the Rayleigh modes in the time-frequency plane. To that end, the signal obtained are processed with the smoothed pseudo-Wigner-Ville distribution.

At last, experimental results on the influence of source position are presented and compared to the Finite Element simulations.

2 Influence of the source and detection position for several adhesion degrees

The influence of the generation and detection positions for several adhesion degrees are studied first through the dispersion curves of the Rayleigh modes that are obtained using Finite Element simulations for four different configurations.

2.1 Finite Element model

The propagation of the surface acoustic waves in a PVC film deposited on an aluminum substrate is modeled using the COMSOL Multiphysics software.

The characteristics of the film and the substrate are presented in Table 1. The thickness of the film has been measured experimentally using a high-precision comparator and the bulk wave velocities using piezoelectric transducers and the pulse-echo method. The thickness of the PVC film is considered as quasi-constant because its maximum fluctuations measured around the average thickness are $2 \mu m$ ($\pm 1\%$).

Table 1 – Characteristics of the materials used for the simulations.

	PVC film	Aluminum substrate
Thickness h	213 μm	10 cm
Density (kg/m^3)	1300	2798
Longitudinal wave velocity (m/s)	1900	6400
Shear wave velocity (m/s)	760	3140

The adhesion between the substrate and the film is modeled by a very thin layer at the interface between the two materials. Its thickness is 0.1 μm and its mechanical characteristics determine the contact conditions following the well-known interfacial stiffnesses model [12-14]. The higher the normal stiffness K_n and the tangential stiffness K_t are, the higher the adhesion is. Three degrees of adhesion are considered, the corresponding stiffnesses values are presented in Table 2. The first degree of adhesion is almost perfect contact, the second degree an intermediate adhesion and the third degree quasi-total disbonding.

Table 2 – Interfacial stiffnesses values used for each degree of adhesion.

Degree of adhesion	$K_n (N/m^3)$	$K_t (N/m^3)$
1	2.10^{16}	1.10^{16}
2	2.10^{13}	1.10^{13}
3	2.10^8	1.10^8

The excitation of the acoustic waves is modeled using a force dipole. The forces applied are tangential to the film surface or the film-substrate interface. The normal displacement of the surface acoustic waves is measured by 201-point probes spaced from each other by 50 μm . By applying a 2D Fast Fourier Transform to the probe signals, the dispersion curves of the Rayleigh mode are obtained.

Four configurations, presented in the Figure 1, are studied for the source and detection positions.

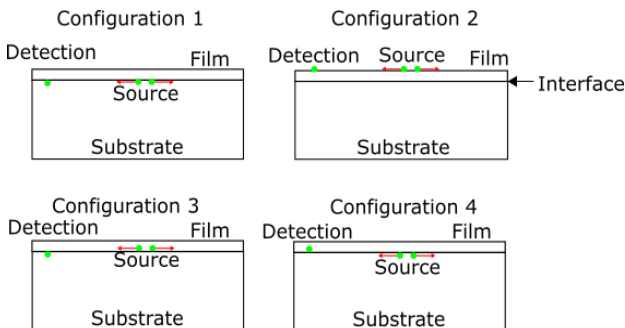


Figure 1 – Configurations of the source and detection positions used in the Finite Element simulations.

In the first configuration, both the generation and the detection are placed at the interface between the film and the

substrate, on the substrate surface. In the second one, both are placed on the film surface. In the third one, both are placed at the interface, but the generation is placed on the film side and the detection on the substrate surface. The fourth configuration is the opposite of the third one: the generation is on the substrate surface and the detection on the film side.

2.2 Rayleigh modes dispersion curves

Figures 2 to 5 show the Rayleigh modes dispersion curves with the three adhesion degrees for each configuration. The black lines correspond to the dispersion curves processed analytically using the Transfer Matrix method of Thomson and Haskell [15-16]. The colormap corresponds to the normalized modulus of the 2D Fast Fourier Transform applied to the simulation results. The black lines in the Figures 2c and 3c correspond respectively to the Rayleigh wave velocity in the aluminum substrate and the Lamb modes dispersion curves in the PVC film.

The same behavior for the Rayleigh modes dispersion curves when the adhesion decreases already obtained in [10] with a PET film on an aluminum substrate are observed for the two first configurations on the Figures 2 and 3. For the first configuration (Figure 2), the excited and detected parts of the Rayleigh modes are around the Rayleigh wave velocity in the substrate. When the adhesion decreases, they merge together to form the Rayleigh wave in the substrate.

For the second configuration (Figure 3), the excited and detected parts of the modes are different than for the first configuration and are observed at lower phase velocities. When the adhesion decreases, they merge together to form the Lamb modes in the film.

For an adhesion almost at the perfect contact, the Rayleigh modes dispersion curves corresponding to the third (Figure 4a) and fourth (Figure 5a) configurations have the same behavior than the one observed in the first configuration (Figure 2a).

For the intermediate adhesion degree (Figures 4b and 5b), the excited and detected parts of the modes are this time a combination between modes observed in the first and second configurations (Figures 2b and 3b).

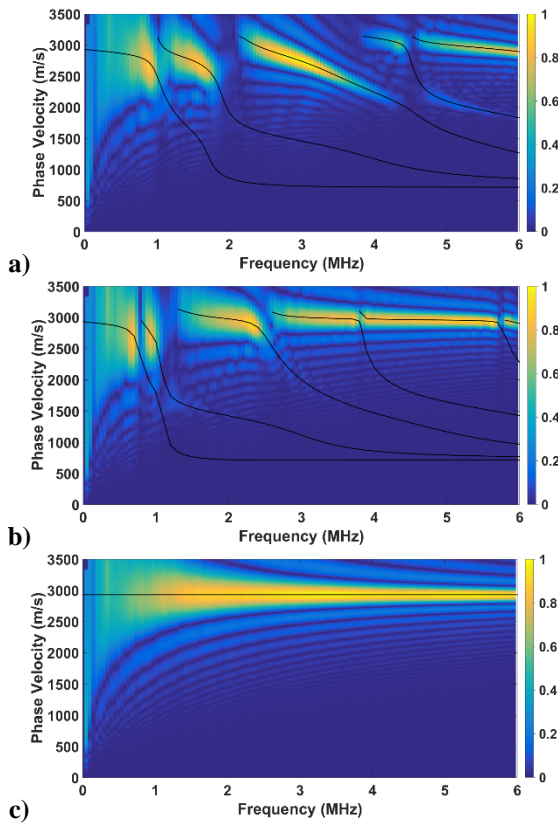


Figure 1 – Rayleigh modes dispersion curves obtained from the FEM for the first configuration in Figure 1. a to c: Adhesion degrees 1 to 3.

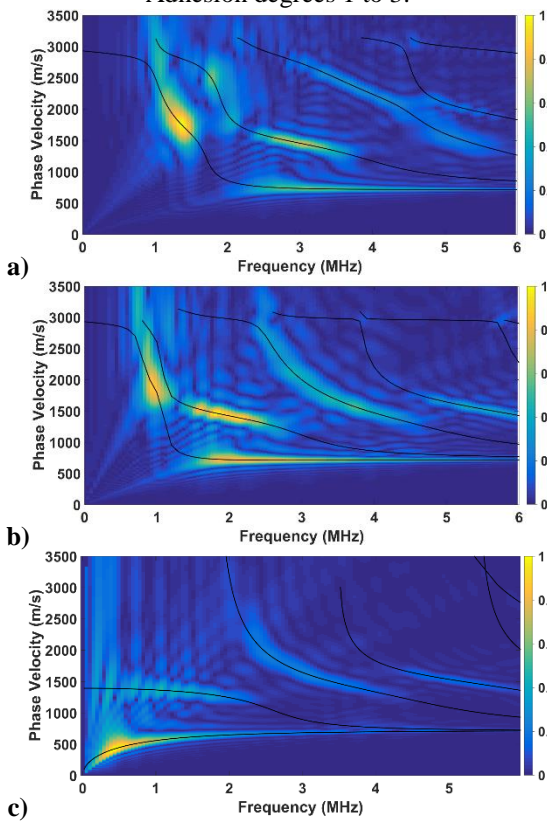


Figure 2 – Rayleigh modes dispersion curves obtained from the FEM for the second configuration in Figure 1. a to c: Adhesion degrees 1 to 3.

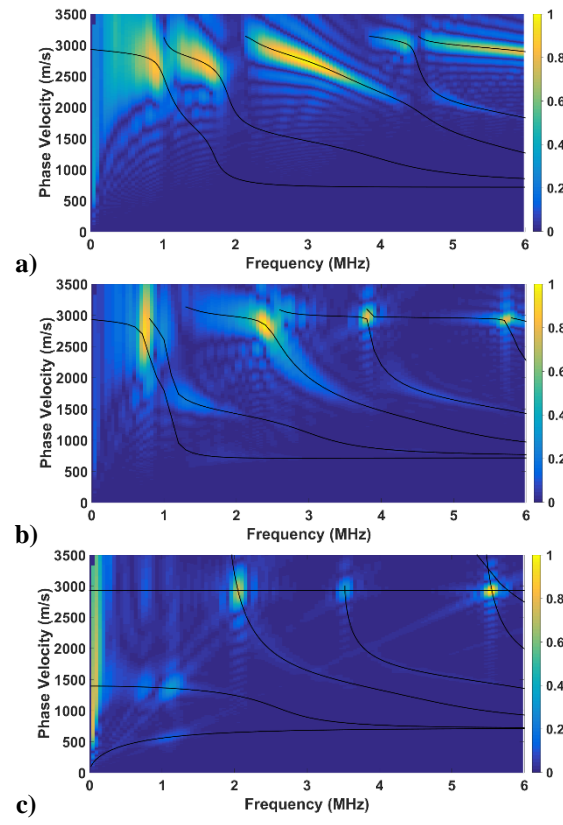


Figure 3 – Rayleigh modes dispersion curves obtained from the FEM for the third configuration in Figure 1. a to c: Adhesion degrees 1 to 3.

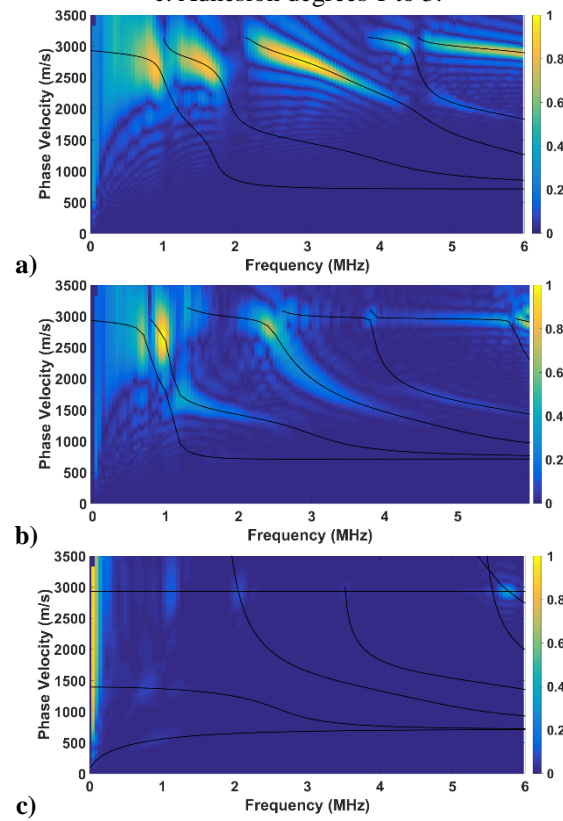


Figure 4 – Rayleigh modes dispersion curves obtained from the FEM for the fourth configuration in Figure 1. a to c: Adhesion degrees 1 to 3.

For example, the low-frequency part of the third mode in Figures 4b and 5b (between ~ 1.5 and ~ 2.5 MHz) is excited in the same way of Figure 2b while the high-frequency part (between ~ 2.5 and ~ 4 MHz) is similar to the one in Figure 3b. The Figures 4b and 5b are approximately the same.

For an adhesion corresponding to a quasi-total disbonding (Figures 4c and 5c), there is nearly no Rayleigh modes that are excited/detected. The only energetic parts obtained are located at the intersection between the Rayleigh wave velocity and the Lamb modes dispersion curves. It can't be observed on the dispersion curves, but the amplitude of the signal obtained by the simulations for this last adhesion degree are 10^4 times weaker for the third and fourth configurations than for the first and second.

It can be inferred from these results that for a source and a detection placed on either side of the interface, regardless of their position in the film or the substrate, the same parts of the Rayleigh modes are excited and detected for an adhesion almost at the perfect contact. When the adhesion decreases greatly, it can be considered that no wave is propagating at the position where the detection is located. For intermediate adhesion degrees, the excited and detected parts of the modes are a combination of those which can be observed when the generation and the detection are both placed on the surface of the film or at the interface on the substrate side.

It means that the parts of the Rayleigh modes that are excited and detected depend on the same time of the position of the generation and the detection (i.e. at the interface or at the film surface) and of the medium in which they are placed (i.e. in the film or in the substrate).

Indeed, by considering that only the source and detection position at the film-substrate interface or at the film surface has an influence, the same results should have been observed for the first, the third and the fourth configurations, which is not the case except for almost perfect contact.

By considering that only the medium in which the source and the detection are placed has an influence, the results observed for the third and fourth configurations for intermediate and very low adhesion degrees are logical, but not the one for the almost perfect contact that should be a combination between the first and second configurations.

3 Experimental study : contact surface and source position

The PVC film used experimentally to be deposited on the aluminum substrate has an interesting characteristic. Just after depositing the film on the substrate by applying a weak pressure, its adhesion is very weak. Over the time, its adhesion increases locally by the appearance of a visible "contact surface" which gradually spreads.

First, an experimental characterization of the influence of this contact surface on the Rayleigh modes propagation is performed using the smoothed pseudo-Wigner-Ville distribution.

Finally, the results of a short experimental study about the influence of the source position are compared to the Finite Element simulations.

3.1 Experimental process

The experimental setup used is presented in Figure 6. A 10 ns Q-switched Nd:YAG laser pulse with a 532 nm wavelength is used to generate the acoustic waves. The beam is focused as a line source, through the transparent PVC film, directly on the aluminum substrate surface. A high precision displacement stage allows us to move the line source at the sample surface. Another displacement stage is also used to move vertically the sample.

The normal displacement of the surface waves is detected using a Mach-Zehnder type interferometer with a power of 100 mW and a bandwidth of 200 kHz – 45 MHz. The laser spot of the interferometer is focused on the substrate surface, outside of the film.

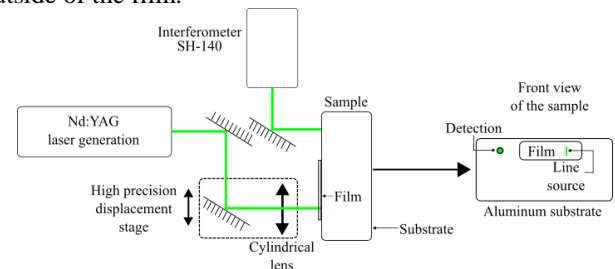


Figure 5 – Laser-ultrasonics setup.

Figure 7 shows the experiments used to characterize the influence of the contact surface on the Rayleigh modes propagation. At time t_0 , a first measurement is performed just after the deposit of the film on the substrate (Figure 7a). Its adhesion is weak and no contact surface can be observed. At time $t_0 + 2$ hours, a contact surface has appeared at the film-substrate interface but it is not located on the propagation path of the surface wave. A second measurement is carried out (Figure 7b).

The sample is then moved up to place the propagation path of the wave on the contact surface and a third measurement is realized. The last measurement is achieved at $t_0 + 4.5$ hours. The contact surface has spread gradually.

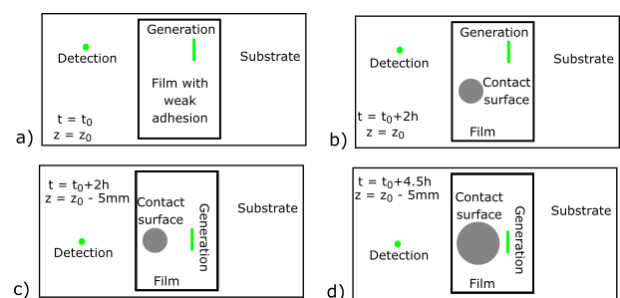


Figure 6 – Experiments allowing to characterize the influence of the contact surface.

3.2 Influence of the contact surface on the Rayleigh modes propagation

Figure 8 presents the signals obtained thanks to the experiments described on Figure 7. Figure 9 shows the normalized moduli of their associated smoothed pseudo-Wigner-Ville distributions.

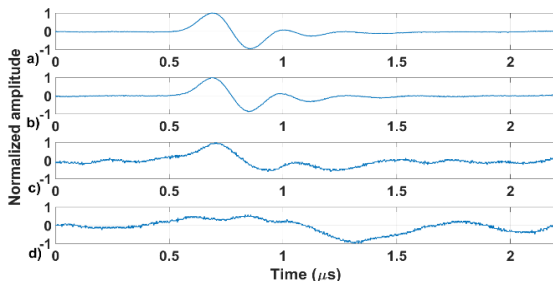


Figure 7 – Signals corresponding to each experiment of Figure 7. a to d: related respectively to Figures 7a to 7d.

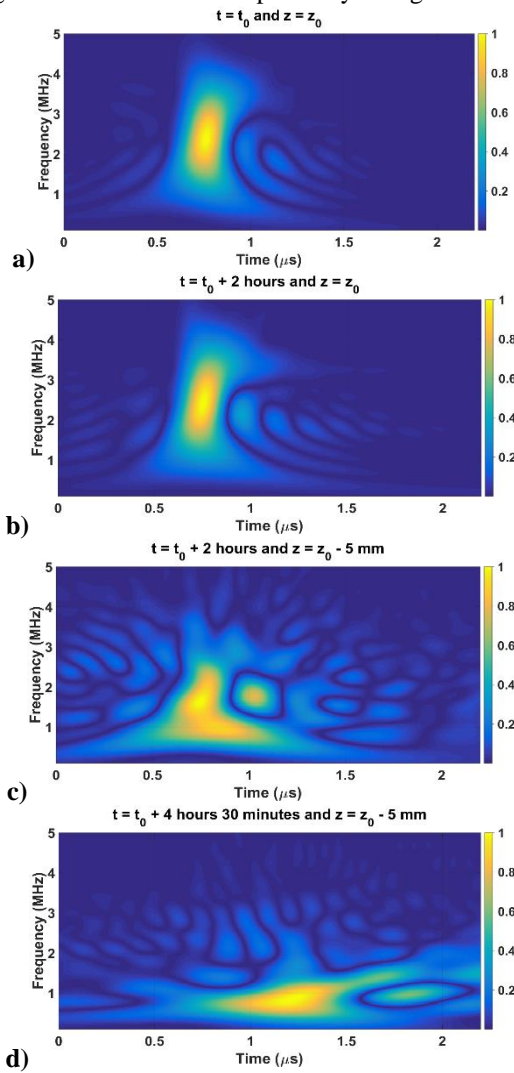


Figure 8 – Normalized moduli of the smoothed pseudo-Wigner-Ville distributions associated to Figure 8 signals. Figures 8 and 9 show the influence of the contact surface on the dispersion of the Rayleigh modes. For a weak adhesion, when no contact surface can be observed on the film (Figures 8a and 9a), a non-dispersive wave is obtained. It corresponds to the Rayleigh wave propagating in the aluminum substrate: the adhesion of the film is too weak to influence the surface wave generated by the laser excitation in the substrate. Two hours after (Figures 8b and 9b), when the contact surface has appeared outside the surface wave propagation path, the same signal is observed. It indicates that the film adhesion local increase has no influence on the Rayleigh modes if they propagate outside the contact surface.

By including the contact surface on the propagation path (Figures 8c and 9c), the surface wave is slightly more dispersive and the energy is located at lower frequencies. The increase of the film adhesion in a small surface is enough to influence the propagation of the surface wave.

When the contact surface increases, and consequently the adhesion of the film (Figures 8d and 9d), the dispersion of the wave is higher and the frequencies observed are lower. The arrival time of the wave is also longer, which means that velocity is lower. This delay increases with frequency.

The Rayleigh modes are more influenced by the film when its adhesion increases. The PVC film widely attenuates high frequencies, it can explain their absence in Figure 9d.

These results show that it is possible to characterize the film adhesion using the dispersion of the Rayleigh modes. Especially, it is possible to determine if a contact surface exists on the propagation path and to characterize its size.

The configuration of generation and detection used for this experiment corresponds to the first considered for the Finite Element simulations. The results obtained experimentally are in good agreement with the expected ones. In this configuration, an increase of the adhesion is associated to an increase of the dispersion of the Rayleigh modes and a decrease of their velocity. The velocity of the high frequency components is lower than the one of the low frequencies. For weak adhesions, the Rayleigh modes merge together to form the Rayleigh wave in the substrate.

3.3 Influence of the source position

Another experiment is performed to study the influence of the source position, in addition to the Finite Element simulations. By depositing a thin layer of black paint at the film surface on a small zone, it is possible to generate the surface wave from the film. Indeed, the source is placed at the film surface instead of at the film-substrate interface.

The laser source is moved using the displacement stage (Figure 6) by 1 mm steps. In this way, two different source positions are obtained. When the laser pulse is focused outside the painted area, the surface waves are generated at the film-substrate interface (on the substrate surface). When the laser pulse is focused on the painted area, the excitation of the surface waves is produced at the film surface. Figure 10 shows the experimental setup used.

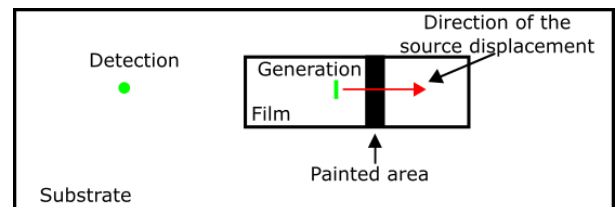


Figure 9 – Experimental setup used to study the influence of the source position.

The experiment is performed for two adhesion degrees. First, for a very weak adhesion (same configuration as the Figure 7a). Second, for a good adhesion, after the contact surface has spread all over the film. Figure 11 presents the results obtained for each adhesion degree. The black signals correspond to an excitation outside of the painted area and the red ones to an excitation from this one (positions 5 to 8).

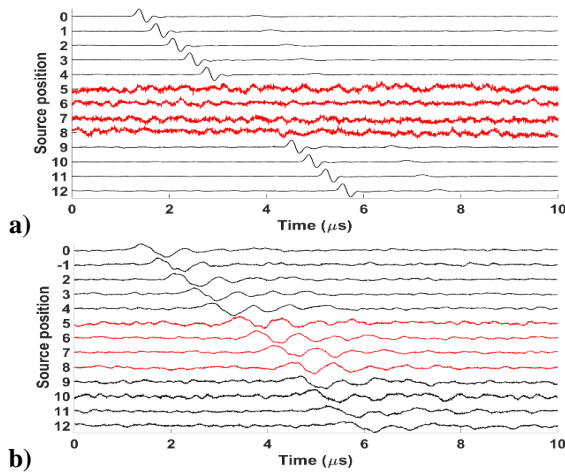


Figure 10 – Signals obtained for different source positions. a: Associated to a weak adhesion. b: Associated to a good adhesion. Black: laser pulse focused outside the painted area. Red: laser pulse focused on the painted area.

It clearly appears that for a weak adhesion (Figure 11a) and a generation at the interface between the film and the substrate, the same signal of Figures 8a and 8b is observed. It corresponds to the Rayleigh wave in the substrate, as seen in Figure 2c.

For a generation on the film surface (source positions 5 to 8), no wave is detected. The configuration of the source/detection position is similar to the third configuration in Figure 1, with an excitation in the film and a detection on the substrate. These results fit well with the ones of Figures 4c and 5c: no wave is detected when source and detection are placed for one in the film and for the other in the substrate.

For good adhesion (Figure 11b), the signals are similar for each source position. It agrees with Figures 2a, 4a and 5a.

4 Conclusion

Through this work, laser-ultrasonics was used to study the influence of the generation and the detection positions of the Rayleigh modes for the study of the film-on-substrate adhesion. Finite Element simulations were first presented to study four different configurations of source/detection position. It clearly shows that both the source position (i.e. at the film-substrate interface or at the film surface) and the medium in which the excitation and the detection are located (i.e. in the film or in the substrate) have an influence.

The sample studied experimentally is composed by a transparent PVC film deposited on an aluminum substrate. By focusing the laser pulse through the film, directly on the substrate surface, the acoustic source is placed at the film-substrate interface. The detection is located outside of the film, on the substrate. The PVC film presents the interesting characteristic to create over the time a contact surface with the substrate in which the adhesion is increased. The influence of this contact surface on the propagation of the Rayleigh modes was studied. Using the smoothed pseudo-Wigner-Ville distribution to represent the dispersion of these surface waves in the time-frequency plane, we showed that it was possible to characterize the existence and the size of the contact surface if it is placed on the propagation path. When no contact surface is on the propagation path, a Rayleigh wave propagating on the substrate is simply

observed. When the contact surface is placed on the propagation path, the larger is the surface, the higher is the dispersion of the Rayleigh modes.

Finally, a short experiment was performed using a thin black paint layer to place the acoustic source at the film surface. For a good adhesion, a similar signal was observed for an excitation located at the film-substrate interface and at the film surface. However, it was not the case for an almost total disbonding. No wave was detected for a generation at the film surface, when a signal corresponding to a Rayleigh wave propagating in the substrate was obtained by placing the generation at the interface. These results were in good agreement with the simulations presented.

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