Application of conoscopic holography to control the melt stirring

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**Up to now, no model or contactless sensor has been available for on-line control of the effectiveness of the flow of the stirring gas in the ladle in secondary metallurgy.
A new method, based on the use of conoscopic holography, has been developed by Arcelor-Aceralia. It measures on line the vibrations in the walls of the ladle and relates them to the argon flow rate. This method is useful for determining the real state of the stirring process, obtaining an accurate index of the process of melt agitation that influences the composition homogeneity and cleanliness.**

■ INTRODUCTION AND OBJECTIVES

A new advanced and breakthrough technology has been developed for on-line control of stirring in secondary metallurgy and installed in Arcelor-Aceralia. This technology has been developed in a project funded by the EU ECSC-Steel program.

On-line quality control of the efficiency of the processes is becoming a key factor for cost minimization in any industry. Full on-line production checking yields many benefits: problems in the process can be solved with rapid feedback, reduced costs due to rejections, reduced customer claims, etc.

Currently, in the industrial process in secondary metallurgy there is no specific and feasible method to verify the stirring of the melt. Mainly, the operator relies on his own experience and on other indirect ways, such as the "open-eye" in the slag, and other operational parameters.

Quality requirements in adjustment, in composition and cleanliness of the melt call for the design and implementation of a new accurate sensor to perform a feasible measure of the stirring. This sensor would take as references the gas flow rate and the induced vibrations of the ladle.

An innovative on-line sensor to measure the stirring and analyze the relation between stirring flow rate and vibrations in a ladle under treatment in secondary metallurgy allows establishing an index of the efficiency of the operations of adjustment. The new developed sensor, based on conoscopic holography, with the support of intelligent tools and image algorithms, is able to determine the stirring in real time. This system, which operates in the real environment of an industrial CAS station facility, allows on-line assessment of the production, detecting deviations of the expected stirring and homogenization.

■ TECHNICAL DEVELOPMENT

The system is a contact-less device that takes profit of the properties of the conoscopic holography.

Conoscopic Holography (CH) is not widely known, so a brief explanation of this technology is presented. CH is a form of incoherent light interferometry, based on the interference that occurs between the ordinary and extraordinary rays into which monochromatic polarized light is divided when crossing a uniaxial crystal. The interference figure is a Gabor Zone Lens that can be captured by a standard CCD camera, where the fringes density is an indication of the distance of the light emitting point.

Subject of a presentation at the 2005 ATS International Steelmaking Conference (Paris, December 15-16, 2005).

Utilisation de techniques d'holographie conoscopique pour le contrôle du brassage en poche

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Jusqu'à présent on ne disposait pas de modèle ou de capteur pour contrôler en ligne l'efficacité du débit de gaz de brassage en poche en métallurgie secondaire. Une nouvelle méthode, fondée sur la conoscopie holographique, a été développée par Arcelor-Aceralia. On mesure en ligne les vibrations de la poche en les corrélant au débit d'argon. Cette méthode permet de suivre le procédé de brassage, avec des indications précises sur l'agitation du bain, facteur déterminant pour l'homogénéité de composition et pour la propreté du métal.

Il s'agit d'un dispositif de mesure sans contact qui utilise les possibilités offertes par la conoscopie holographique. Cette méthode de mesure est une variante d'interférométrie en lumière incohérente utilisant une source monochromatique polarisée transmise par l'intermédiaire d'un monocristal. La densité des franges d'interférence traduit la distance à la source. Les franges peuvent être enregistrées avec une caméra CCD.

Les travaux ont été réalisés sur une station CAS de métallurgie secondaire, avec brassage par gaz inerte à travers un bouchon poreux. Les seuls paramètres classiquement contrôlés pour ce process sont le débit et la pression du gaz. La porosité du bouchon peut affecter l'efficacité du brassage qui n'est l'objet que d'une estimation visuelle par l'opérateur.

Les méthodes fondées sur une observation automatisée de la surface du bain n'ont pas été retenues. En effet, il faudrait placer une caméra à l'intérieur de la cloche pour pouvoir observer la surface libre du métal, ce qui pose des problèmes de tenue à haute température et d'accessibilité pour la maintenance.

Par contre les mesures de vibrations sans contact permettent d'utiliser le même équipement sur plusieurs installations et ne demandent qu'un entretien réduit. Il restait à faire la démonstration de leur efficacité dans un environnement industriel.

Un dispositif de conoscopie holographique a donc été installé sur le chariot d'une station CAS pour établir, en conditions industrielles, une relation entre les vibrations et l'efficacité du brassage.

Des essais préalables ont été réalisés en laboratoire pour établir les avantages du conoprobe par rapport à un accéléromètre classique : meilleure précision et mesure directe des amplitudes.

Les essais industriels ont été réalisés sur le chariot du CAS d'Aceralia à Avilès. Le conoprobe utilise une focale de 75 mm avec une précision de 10 µm avec une distance de travail de 70 mm par rapport à la surface observée. La surface observée sur le chariot est une surface plane et le système d'acquisition des données est commandé à distance.

les fréquences les plus représentatives du brassage se situent entre 1 et 50 Hz. Une relation dynamique a été établie entre le brassage et la densité spectrale de puissance dans ce domaine de fréquences. En particulier, il existe une relation linéaire entre la pression de gaz et les vibrations.

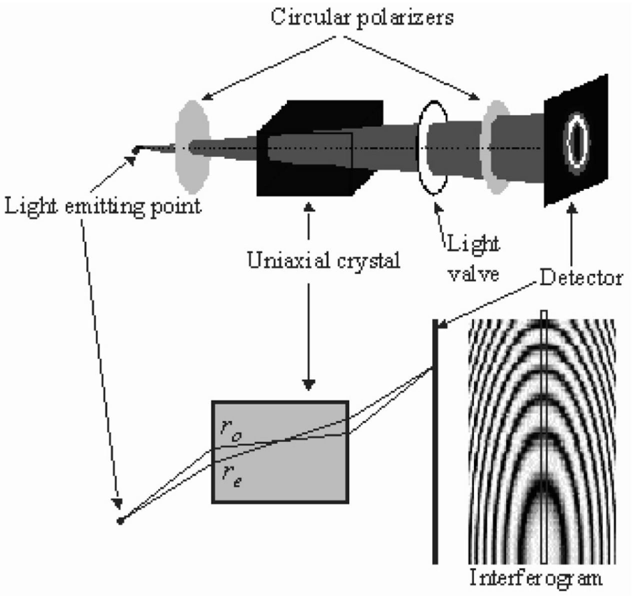


Fig. 1 - Physical fundamentals of conoscopic holography.

Fig. 1 - Principes de la conoscopie holographique.

Vibrations induced by the stirring provoke variations in the distances from the wall of the ladle to the sensor. In the basic configuration, the conoscopic sensor measures the distance variations of a flat surface attached to the ladle car, at a rate of 500 Hz. An automatic cycle has been developed so the computer starts logging data only when the target is in range, and stops logging when the target gets out of range.

This research project has been focused on the CAS station (Composition Adjustment Sealed) where the liquid steel is stirred by means of gas bubbling via a bottom porous plug. Commonly, only input parameters related to stirring are known: flow rate and pressure of the injected gas. Changes in process conditions, mainly the actual porosity of the porous plug, produce changes in the real value of the stirring that are evaluated by the visual estimation of the operator. It is not possible to establish a direct relation of cause-effect among gas injection, bubbling and stirring.

Two main approaches have been envisaged in order to monitor real stirring. Firstly, the study of the surface of the bath by means of machine vision techniques that can be used to correlate the behaviour of surface patterns with the stirring being produced. The second approach has been to analyse the vibration of the ladle; the amplitude and frequencies of the vibration can give an indication of the efficiency of the stirring. Both approaches are not mutually exclusive but can be complementary.

For the machine vision approach, the main problem is the position of the snorkel on the top of the bath *(fig. 2)*. Inside the snorkel *(fig. 2 a)* the steel surface will be free, whilst in the external part *(fig. 2 b)* mainly slag will be seen. This means that looking inside the snorkel will give better information than outside. The problem is the placement of the sensor, that must be on the top of the snorkel, so in a very high temperature place and with difficult access. Installation, cooling and maintenance of this equipment is a very important fact to be considered. In the other hand, the camera for the external view is easier to install and has less maintenance problems.

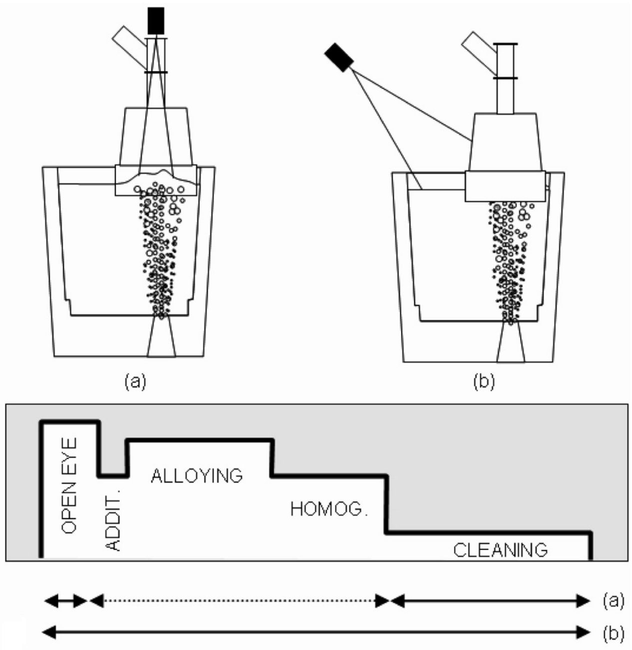


Fig. 2 - Alternatives for machine vision approach: CCD camera placed (a) inside and (b) outside the snorkel.

Fig. 2 - Méthodes potentielles d'observation de la surface du bain : caméra CCD à l'intérieur (a) ou à l'extérieur (b) de la cloche.

For the vibration measurement approach, several problems have to be solved: the temperature of the ladle shell, slag splashes, the cycle of work of the ladles, etc. A non-contact measurement device would have easier application than a contact technology, since the same sensor could be used for all the ladles (what reduces cost and improves efficiency) and the equipment could be easily cooled and protected from dumps. The drawback for non-contact technologies is that they have not been sufficiently tested in such complex environments. A novel non-contact measurement technology called Conoscopic Holography has been selected as a good approach in complex environments. At present, this technology provides measurement of distance variations of several microns at up to 850 Hz rate with a standoff of more than 100 mm.

As the vibration measurement approach looks to be more interesting in terms of installation requirements, maintenance and upgrade, research was oriented to the development of a demonstration prototype working in a steel plant. From the characteristics of a CAS station it can be inferred that the vibration sensing for stirring monitoring can be done on three possible elements: snorkel, ladle and car. The first and the second options require a longer stand-off between a contactless sensor and the vibrating element. This distance can be reduced installing a quite complex supporting structure. On the other hand, the vibration measurement in the car is easier, taking into account that a portion of the transfer car is out of

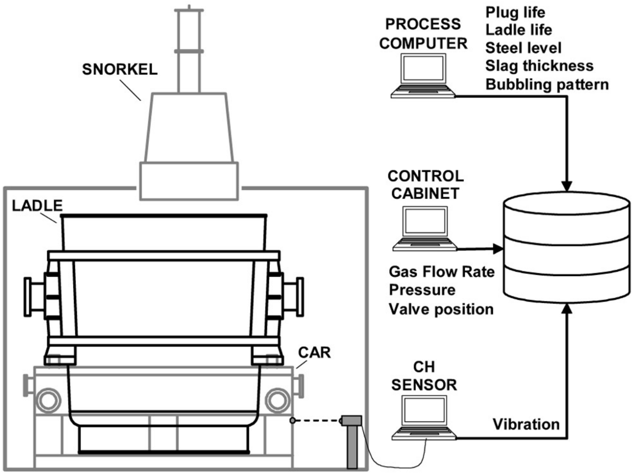


Fig. 3 - Overall description of the scenario.

Fig. 3 - Description globale du scénario.

the tunnel of the CAS station where the ladle is located during the treatment. However, at ground level, the tunnel and its surroundings present some risks as slag splashes, car displacements or crane operation. For this reason, special attention has been paid to safety restrictions. In any case, the presence of researchers in the tunnel area has been minimized and an almost stand-alone system has been designed.

Simultaneously, signals from the process (gas flow-rate, gas pressure, gas valve aperture) are registered with a data-logger. Finally, other relevant parameters from the process are added off-line (steel level, life of the porous plug, slag level, etc.). All the relevant data are grouped in a database and processed in order to establish relations between them. The overall process is indicated in *figure 3*.

One of the most significant advantages of Conoscopic Holography technology is that, with a single sensor, only changing the front lens makes it possible to obtain different ranges and resolutions of measurement.

During the lab scale trials and preliminary industrial tests and investigations, lenses with 25 and 75 mm focal lengths have been used mainly.

In the first stages of the research, tests for vibration measurement have been made on other equipments, as electric motor, or devices under vibration, with very good results, with a clear relation between rotation speed and vibrations in the shell.

The objective of the developments has been to determine whether a non-contact vibration measurement system based on Conoscopic Holography technology is suitable for the application, meaning that:

- The system detects vibrations in the ladle car.
- The measured vibrations have a relation with the stirring parameters, that is, they are meaningful for the final objective of detecting the real stirring.
- The system is robust and can work in industrial environment.

The system is completed with a procedure for extensive test, in order to obtain statistically meaningful data from the sensor and the process, and try to establish the relations between them. For this purpose, a fully automatic vibration acquisition system has been developed and tried in the plant conditions, as well as a system for data logging of the process parameters. The results from both are merged using a specific tool, where it is possible to compare and elaborate statistics. For the comparisons and statistics, specific software has been coded to extract the data from the database and perform these calculations.

■ LABORATORY TEST OF SENSORS

In order to validate the usability of Conoscopic Holography (CH) in vibration measurements, the oscillations of a vibrating surface were measured using this technique. CH is a form of incoherent light interferometry, based on the interference that occurs between ordinary and extraordinary rays into which polarized monochromatic light is divided when crossing a uniaxial crystal.

When the monochromatic light emitted or reflected by a point is passed through the Conoscope, an interference Gabor Zone Lens figure is obtained, and it can be captured by a standard CCD camera. The frequency of the fringes present in the interferogram is related to the distance of the illuminated point. Once the interferogram has been processed, the distance of the point can be obtained. The basic scheme of the needed setup, called Conoscope, is shown in *figure 4*.

The light for illuminating the point is provided by a laser source installed inside the sensor *(fig. 5)*. A sensor configured like this is called Conoprobe.

This technique has many advantages: it is completely collinear and very accurate; the range and consequently the accuracy of measurement can be easily changed by simply using the requi-

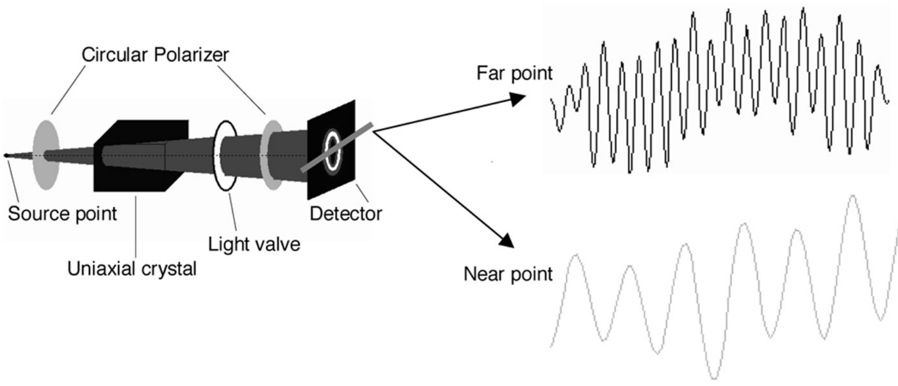


Fig. 4 - Configuration of a conoscope.

Fig. 4 - Configuration d'un conoscope.

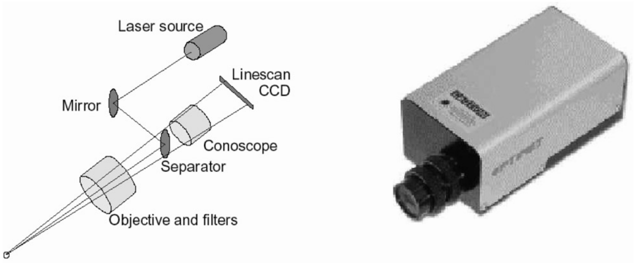


Fig. 5 - Configuration and external view of a conoprobe.

Fig. 5 - Configuration et aspect extérieur d'un conoprobe.

red lens; it can measure surfaces with a slope of nearly 90º. There are different combinations of range, stand-off and resolution for several lenses. In this research, the goal is to have good sensitivity to detect the relevant vibration features and enough standoff to cover the car positioning tolerance.

A huge amount of lab tests were performed to validate the sensitivity of CH against common accelerometers. For this purpose, a vibrating surface was constructed by connecting a non-balanced power source to a 3-phase motor: In this way, the vibrations are higher as the source is less symmetrical. An accelerometer was placed in the casing of the motor, and this place is measured with a Conoprobe (CH sensor) using different lenses: 25 mm, 75 mm, and 150 mm. To be noted that the output from accelerometers and the Conoprobes have different physical units: accelerometers measure acceleration and Conoprobes measure distance.

When one phase input of a 3-phase electric motor is turned off, a higher amplitude vibration, with 100 Hz main frequency, becomes present. Using a 25 mm Conoprobe, the variation of distances due to the different vibrations can be clearly monitored *(fig. 6)*.

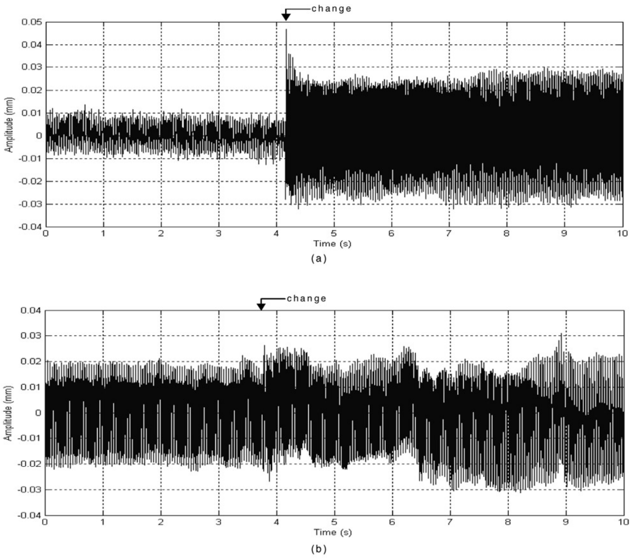


Fig. 6 - Signal of measured vibration with (a) 25 mm lens and (b) 75 mm lens.

Fig. 6 - Signal d'une vibration obtenu avec une focale de 25 mm (a) et de 75 mm (b).

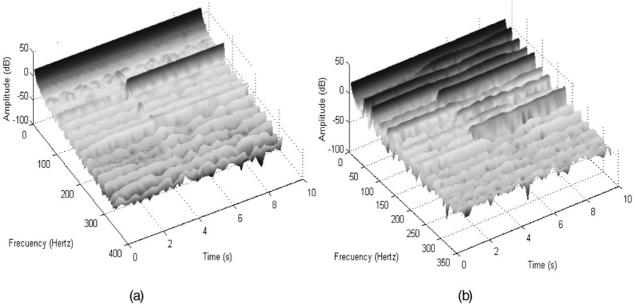


Fig. 7 - Spectogram of measured vibration with (a) 25 mm lens, (b) 75 mm lens.

Fig. 7 - Spectre de la vibration enregistrée avec une focale de (a) 25 mm, (b) de 75 mm.

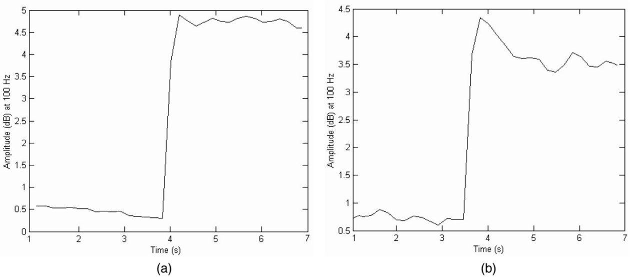


Fig. 8 - Amplitude for the 100 Hz main frequency with (a) 25 mm lens and (b) 75 mm lens.

Fig. 8 - Amplitude correspondant à la fréquence principale de 100 Hz, avec une focale de (a) 25 mm, (b) de 75 mm.

The new 100 Hz component becomes manifest in the frequency domain using a spectrogram *(fig. 7 a)*, *(fig. 8 a)*. When using lenses with higher stand-off and range, and thus lower resolution, the results become less clear *(fig. 7 b)*, *(fig. 8 b)*, *(fig. 9 b)* showing the same example as before, in this case

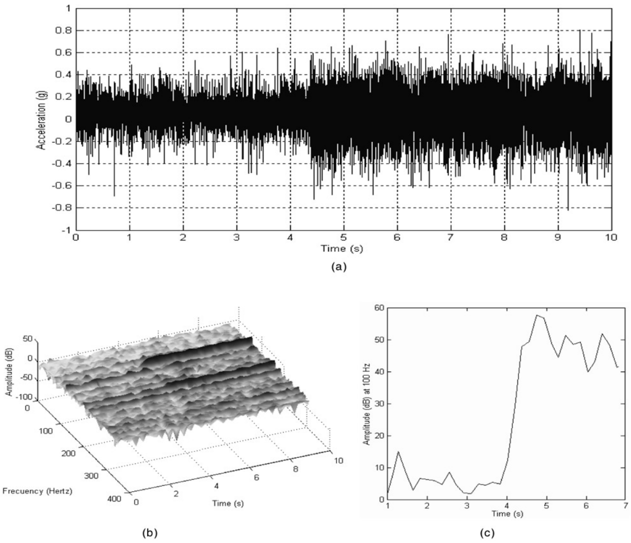


Fig. 9 - Results obtained with the accelerometer: (a) signal, (b) spectrogram, and (c) amplitude for the 100 Hz component.

Fig. 9 - Résultats obtenus avec l'accéléromètre : (a) signal, (b) spectre, (c) amplitude de la fréquence 100 Hz.

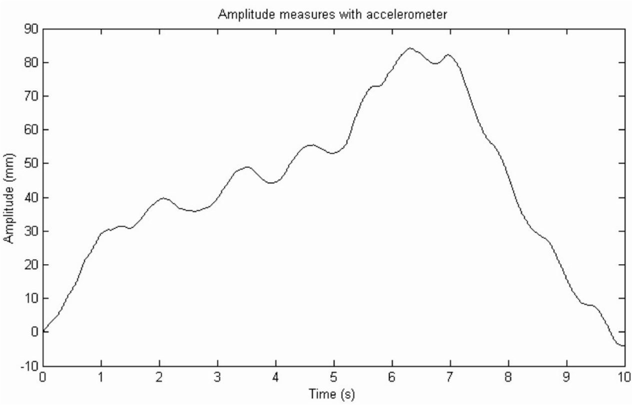


Fig. 10 - Computed amplitude obtained by integration of the signal from the accelerometer.

Fig. 10 - Amplitude calculée à partir du signal de l'accéléromètre.

with a 75 mm lens. For this amplitude of vibration, the time domain looks to have no information, but the frequency domain again shows the difference for the 100 Hz harmonic.

The results obtained with the accelerometer in the same trials are represented in *figure 9*. Again, in the frequency domain, the results become more evident with the presence of the 100 Hz harmonic in the moment of the change.

The comparison of the conoscopic sensor results with those coming from a conventional accelerometer can be done in two ways: differentiating twice the distance signal from the Conoprobe to obtain acceleration, or integrating twice the signal from the accelerometer to obtain distance. When using the first approach, the solution is good and the results are comparable. When trying the second approach, as the errors in the integration are accumulative, the results from the accelerometer differ substantially of the real distance data *(fig. 10)*.

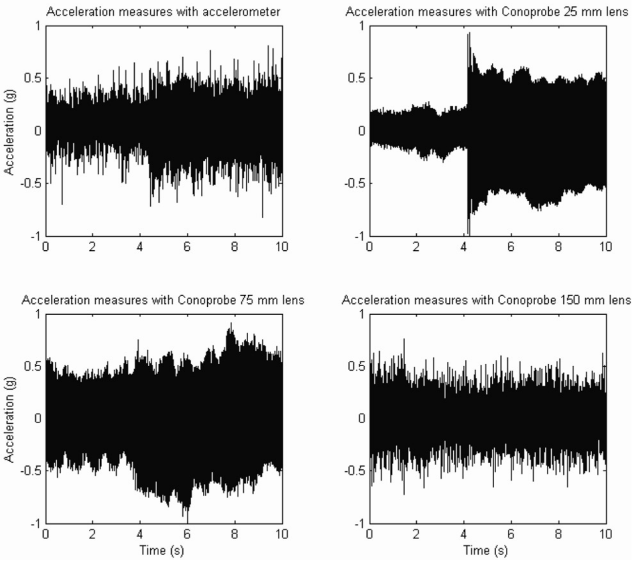


Fig. 11 - Comparison of results for different lenses and the accelerometer.

Fig. 11 - Comparaison des résultats obtenus avec différentes focales et avec l'accéléromètre.

It gives an advantage for the Conoprobe: the amplitude of the vibration is measured directly, a more reliable procedure than a double integration.

Summing up, lab tests showed that a solution with a high definition Conoprobe can give more reliable information than a conventional accelerometer, providing direct amplitude data with higher accuracy. The selection of the probe lens will depend on the amplitude of the vibration to be measured, in order to combine enough stand-off and high range with enough accuracy. Anyway, in the frequency studies lower resolution lenses could be used with results similar to the accelerometer.

Figure 11 shows how the 25 mm Conoprobe appears as much more sensitive, and the 75 mm lens is in the range of the accelerometer.

■ TEST OF SENSORS IN INDUSTRIAL PLANT

The lab tests showed that the use of a high definition Conoprobe can be suitably employed to obtain information on surface vibration. However, it was seen that the most adequate configuration of the Conoprobe would depend on the real environment and the real vibrations to be measured in an industrial environment.

The accuracy needed for the measuring probe depends on the amplitude of the vibrations to be measured. Less accuracy needed leads to a much simpler design: higher measurement range, lower dependence on external conditions and higher stability of the system. As the configuration of the probe depends on the amplitude of the vibration to be measured, and this oscillation were initially unknown, it was necessary to investigate these

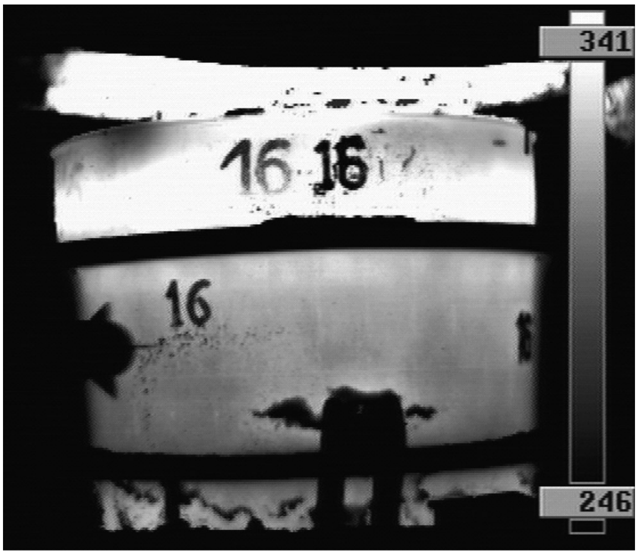
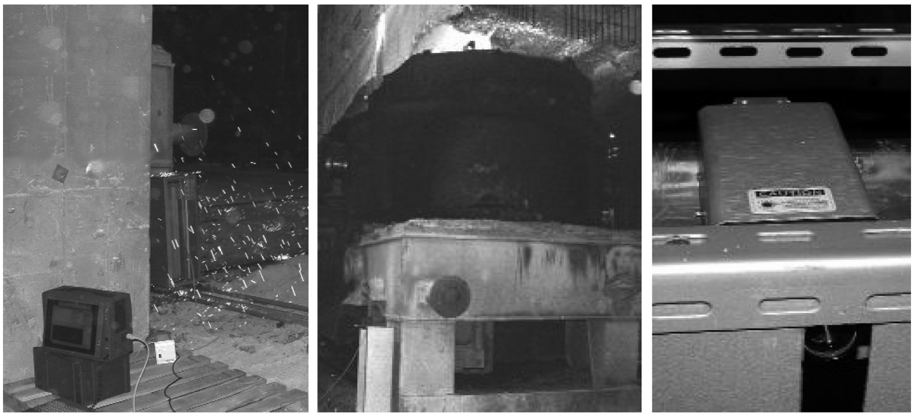


Fig. 12 - Thermographic image of the ladle shell during CAS treatment.

Fig. 12 - Thermographie de la coque de la poche au cours du traitement CAS.



(a) (b) (c)

Fig. 13 - Trials with Conoscopic Holography: (a) side view, showing acquisition computer remotely operated; (b) front view, showing ladle, car and the first prototype; and (c) inside view of the prototype.

Fig. 13 - Essais en conoscopie holographique : (a) vue latérale avec l'ordinateur à télécommande, (b) vue de face avec la poche, le chariot et le premier prototype, (c) vue de l'intérieur du prototype.

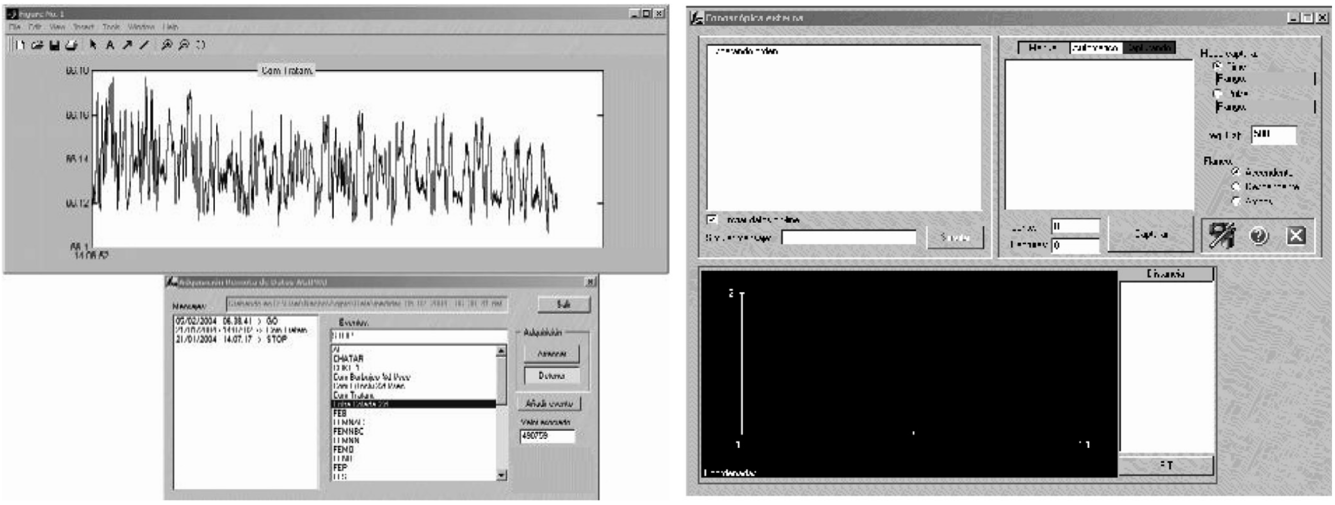
values to validate the suitability of the system and to design an operating prototype in real industrial environment. In other words, defining the field of existence of the variable to be measured, i.e. the range of variation of frequencies.

The frequency range of the vibrations to be monitored is important too. Since the probe is able to work at 850 Hz maximum, only frequencies less than 425 Hz can be monitored. The higher frequencies are naturally filtered by the sensor without a need of anti-aliasing filters, as the distance variations during the acquisition time are averaged.

Furthermore, it was also important to pre-test the behaviour of the Conoprobe in the real plant conditions with special regard to the surrounding noises and the harsh environment conditions. A thermographic study of the environment was carried out, in order to evaluate the required thermal protection to maintain the sensor within the range of allowed temperatures. A temperature map of a ladle during the stirring process *(fig.12)* shows the actual temperature of the shell to be around 300 ºC. It also shows that the target should be placed, regarding this parameter, as close as possible to the floor, where the temperatures are lower.

In order to fulfil the above-mentioned requirements, preliminary test of sensors were carried out in the CAS station of the LDA steel plant in Aceralia - Avilés. It was opted to measure vibrations on the wall of the ladle transfer car instead on the ladle wall directly. This decision was based on the following facts:

- It requires only one target (cleaned surface) as reference frame of vibrations to be mounted in the car. If the measurement is performed on the ladle wall, it will require mounting one of these targets in every ladle in use. Furthermore, if the target is placed in the car it will be more easily kept clean.
- The environment is less aggressive at car level than at ladle level: lower temperature, less hot splashes, etc.
- Better accessibility and better safety conditions for researchers and operators taking into account that a portion of the transfer car is out of the tunnel during the treatment. No need of scaffolding or complex supporting structures.
- It was taken into account that a complete validation of a system for ladle stirring monitoring would require extensive plant testing and this testing should be done with minimum interference with the normal production processes and practices. It was agreed with production and maintenance staff that this emplacement will cause no interference at all with



(a) (b)

Fig. 14 - Acquisition software: (a) remote monitoring screen and (b) acquisition module screen.

Fig. 14 - Logiciel d'acquisition : (a) vue d'écran de télécommande, (b) vue d'écran du module d'acquisition.

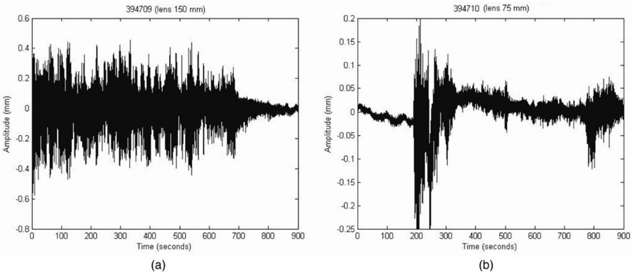


Fig. 15 - Comparison of acquired signals: (a) heat 394709 with 150 mm lens and (b) heat 394710 with 75 mm lens.

Fig. 15 - Comparaison des signaux enregistrés : (a) coulée 394709 avec une focale de 150 mm, (b) coulée 394710 avec une focale de 75 mm.

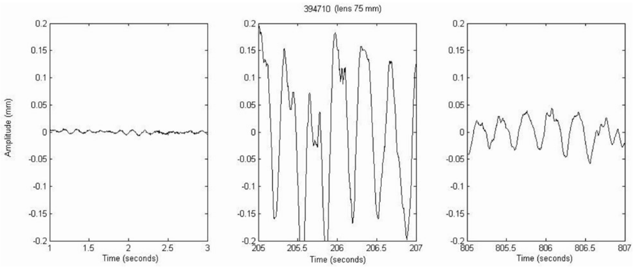


Fig. 16 - Changes in amplitude and frequency of vibrations during a treatment.

Fig. 16 - Changements d'amplitude et de fréquence des vibrations en cours de traitement.

normal production process and certain maintenance operations as, for example, the change of snorkel.

A target machined surface was installed in a side of the ladle car in order to reduce measurement errors. A steel protection cabinet with positioning guides was constructed and a Conoprobe was placed inside. The system was located at ground level, avoiding any interference with the transfer car path. Since the temperatures in the area are rather low, no special cooling was needed and the steel box ensured an environmental temperature at the sensor not higher than 35 ºC. The computer for data acquisition was placed in a safer position, behind one of the protection walls of the tunnel. *Figure 13* shows the system in operation during the trials.

In order to minimize the presence of research personnel at ground level the acquisition system was operated and monitored remotely by means of UDP/IP sockets communications. This allowed also monitoring the results in the control room, so the different actions in the treatment are known in real-time and can be related with the vibration conditions monitored. Special purpose software was used. *Figure 14* shows some screens of this computer program.

Initially, the vibration of the transfer car was measured, registering the distance oscillations with the CH system at a rate of 500 Hz during 15 minutes; this gave a total of around 450,000 values sampled for each heat. The signals obtained with 150 mm and 75 mm lenses are shown in *figure 15*.

As the 150 mm lens provided not enough resolution to mark out different stages during the treatment, the results were rejected. On the other hand, the acquisitions performed with the 75 mm lens clearly revealed the pattern of the CAS treatment. *Figure 16* shows the details of the signal acquired with 75 mm lens for different stages of the treatment; the changes in amplitude and frequency are evident.

Therefore, initial plant tests of sensors allowed to take a picture of the involved frequencies and amplitudes and to probe the validity of the method for registering the stirring process during ladle treatment. Based on these results, the vibration measurement system was configured with the following characteristics:

- Conoprobe sensor with 75 mm lens: this gives a maximum acquisition frequency of 850 Hz, a measurement field of 18 mm, a stand-off of 70 mm from the measured surface, an absolute precision of 10 µm and a static resolution lower than 1 µm. Sensors with lower focus lengths require shorter stand-offs that can interfere with the movement of the car, and sensors with higher focus lengths have worst resolutions without improving the emplacement characteristics.
- Sensor pointing to a flat surface in the side of the ladle car: this decision was taken for operational reasons, as this is the easier access point and with the lower temperature. The vibrations in the ladle due to the bubbling must be transmitted to the car, resulting in distance variations that are measured by the sensor.
- Remote operation and monitoring of the acquisition system: by means of UDP/IP sockets communications. This allows monitoring the results remotely, for example, in the control room, so the different actions in the bubbling are known in real-time and can be related with the vibration conditions monitored.

With this vibration measurement system, more trials were performed and useful initial results were extracted. *Figure 17* shows the acquired signal and the spectrogram obtained through FFT.

The different stages of the treatment are clearly marked in the diagrams, mainly relevant in the medium-higher frequencies distribution. Even some special events, as temperature measurement of the melt, were slightly detected by the system. Frequencies at 8-9 Hz, and 22-26 Hz look to be the dominant at low gas flows (cleanliness bubbling).

This preliminary vibration measurement system was tested in more than 30 heats grouped in five campaigns, with an appropriate minimum number of heats each one. Non-contact measurement of the vibration was made during CAS treatments together with the acquisition of analogue signals from the process (gas flow-rate, gas pressure, gas valve position) with a data-logger. Finally, other relevant parameters from the process were added off-line (steel level, life of the porous plug, slag level, etc.). All the relevant data were grouped in a database and processed in order to establish relations between them.

The raw data from the Conoprobe has to be filtered, eliminating from corrupting noise, and then adequately processed to obtain a parameter that reflects the real stirring in the bath *(fig. 18)*.

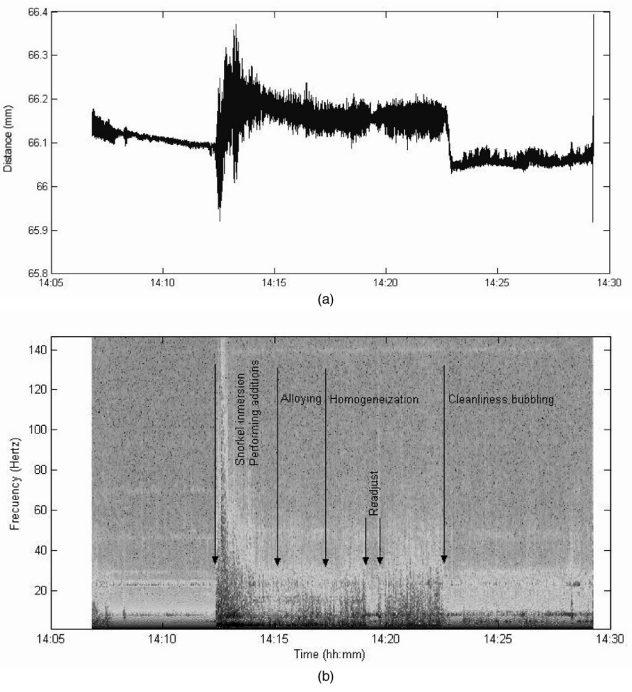


Fig. 17 - Vibration diagrams during a complete CAS treatment (a) signal and (b) spectrogram.

Fig. 17 - Diagrammes des vibrations au cours d'un traitement CAS (a) signal, (b) spectre.

The study of frequencies of the signal from the real plant conditions reveals that the main distance variations occur at very low frequencies, from 1 to 50 Hz, being the main frequency around 3 Hz.

This means that a good parameter for vibration monitoring may be the accumulated power of the signal around these frequencies (power spectral density). At the same time, this value should eliminate the major part of the noise.

A dynamic relation between this measurement of the stirring and the process parameters has been established. From the trials performed, the stirring looks to follow more directly the gas pressure variations than the flow rate, being aware that both are closely related. The results indicate a linear relation between the vibration in the low frequencies (3-30 Hz) with the gas pressure or, in other terms, a quasi first-order relation with the gas flow rate. This looks to be consistent with the theory: when the gas flow rate changes abruptly, both the gas pressure and the movement inside the bath start to vary more slowly to their new stationary values *(fig. 19)*. This seems consistent with the real behaviour of a pneumatic circuit when the gas flow rate changes abruptly both the gas pressure and the movement inside the bath start to vary more slowly to their new stationary values.

Optimal CH sensor configuration was further investigated during the first plant tests. From the point of view of CH, it is well known that shorter lenses give higher accuracy with smaller depth of field and stand-off. *Table I* summarizes the precision, stand-off and depth of field for the main lenses applicable. The lens used in the first trials was 75 mm but, in order to improve sensitivity, a 25 mm lens was also tried. This

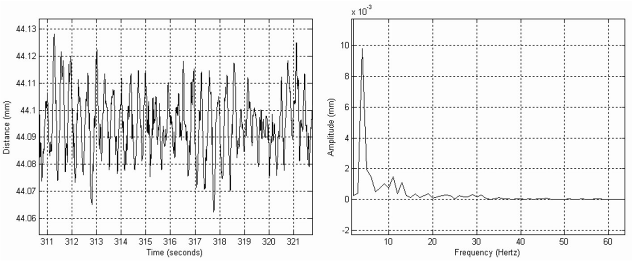


Fig. 18 - Raw signal from the Conoprobe and frequency components.

Fig. 18 - Signal brut du Conoprope et fréquences principales.

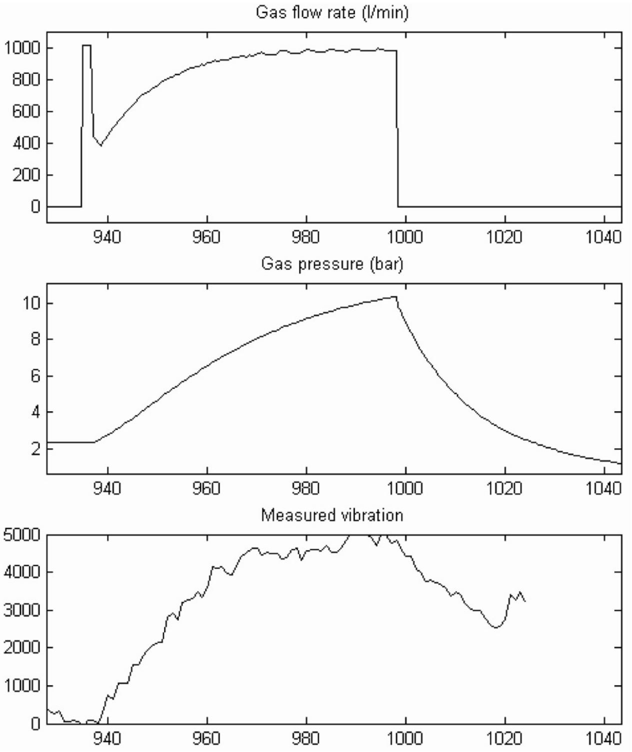


Fig. 19 - Relation between gas flow rate, gas pressure and amplitude of the vibration measured with a Conoprobe with 75 mm lens. Vibration measured appears to follow the gas pressure, with a 1st order dynamic relation with the gas flow rate.

Fig. 19 - Relation entre le débit de gaz, sa pression et l'amplitude de la vibration mesurée avec un conoprobe de focale 25 mm. La vibration correspond la pression et suit une relation dynamique d'ordre 1 avec le débit.

TABLE I: Selection of conoscopic lenses.

TABLEAU I: Sélection des lentilles conoscopiques.

Focal length (mm)	16	25	50	50 ext	75
Static resolution (µm)	<0.1	<0.1	<0.1	<0.1	<0.1
Precision (µm)	<2	<3	<6	<6	10
Reproducibility	0.15	0.4	1	1	2
Working range (mm)	0.6	1.8	8	8	18
Standoff (mm)	12	15	42	85	65

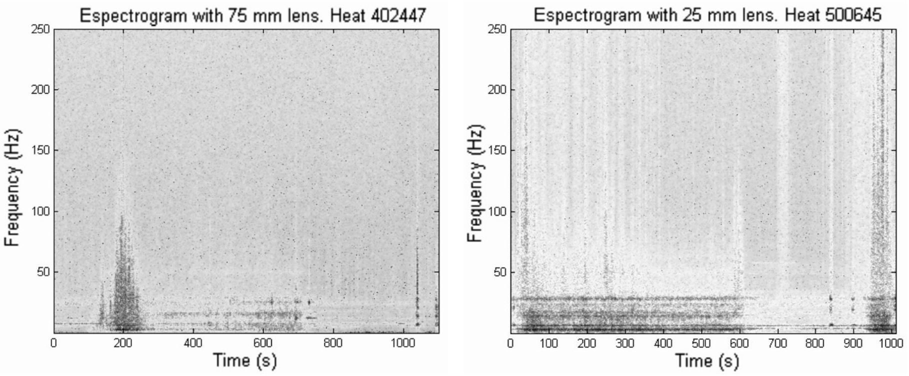


Fig. 20 - Spectrogram for two different heats obtained with (a) 75 mm lens and (b) 25 mm lens.

Fig. 20 - Spectres de deux coulées différentes enregistrés avec une focale (a) de 75 mm et (b) de 25 mm.

on-line test revealed the difficulty, even impossibility, of a manual focusing due to the small working range. To overcome this problem a special auto-focusing stand was developed. With this improvement the resulting system can operate with a much more sensitive lens of 25 mm and is fully automated, including the detection of the car and the dynamic adaptation to changes in the lateral position of the car.

■ RESULTS

Many trials with the 75 mm lens indicate a linear relation between the vibration in the low frequencies (3-30 Hz) with the gas pressure or, in other terms, a quasi first-order relation with the gas flow rate. This looks to be consistent with the real behaviour of a pneumatic circuit when the gas flow rate changes abruptly, both the gas pressure and the movement inside the bath start to vary more slowly to their new stationary values.

For the first C.H. based prototype, a 75 mm lens was used. This was very useful for the ease of the plant installation for two reasons:

- The stand-off for this lens is 65 mm, giving a reasonable security distance from the ladle car. This permits to use a static system.
- The long working range of 18 mm around the stand-off distance ensures that the target will always be in the range when the car is again in position.

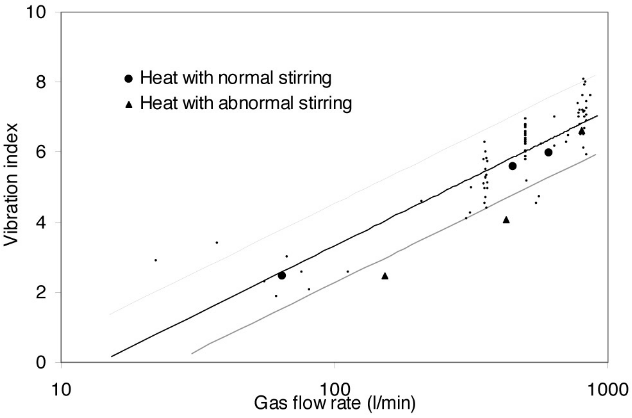


Fig. 21 - Correlation between vibration and gas flow rate; heats with abnormal stirring can be identified.

Fig. 21 - Corrélation entre la vibration et le débit de gaz ; les coulées avec brassage anormal peuvent être identifiées.

In lab trials performed with ladle scale models it was seen that the frequencies involved were higher. This appears to be the reason why the vibrations were better measured in real plant ladles than in scale models.

Trials have been made in order to correlate the relevant process parameters affecting the stirring and the measurement (porous plug, slag, mass of steel, etc.) with the actual vibration measured. As an example of the significance of the measurements of the sensor it was found a relation mainly with the lifetime of the porous plug.

Different environments for measurement require minimum adaptation in the optics. Comparison of spectral distributions obtained with 75 mm and 25 mm lens, on two different heats can be seen in *figure 20*. The 25 mm lens makes the system much more sensitive in a broader range of frequencies.

The static relations between vibration, gas flow rate and gas pressure have been investigated. It has been observed that the dispersion of the results is particularly high for the cases of pressure / flow-rate and vibration / pressure. By contrast *(fig. 21)* the correlation between vibration and gas flow rate presented a clear logarithmic tendency with less dispersion. It has been statistically shown that problematic heats in the stirring context fall below the 90 % percentile curves.

■ CONCLUSIONS

Conoscopic Holography looks to be an interesting approach for vibration monitoring at low frequencies, between 0 and 50 Hz, where the sensitivity of other sensors decreases. Low vibration frequencies (between 0 and 30 Hz) in the car appear to be directly related to the gas pressure or, in other terms, to be related by a first order transfer function with the input gas flow rate. High vibration frequencies in the car cannot be adequately obtained with C.H. sensor. With accelerometers, it can be seen that they are more related to the gas flow rate, but not with the movement inside the ladle. Following the previous conclusions, it appears as an important item for the project to determine which frequencies are more meaningful to know the real stirring in the bath.