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Extended summary

Quality Control Agent: Self-Adaptive Laser Vibrometry for on-line Diagnostics

Curriculum: Ingegneria Meccanica e Gestionale

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Abstract. Vibration testing is a well established procedure for assessing the conformity to specifications of a variety of products, which contain moving parts. Typically at the end of an assembly line, a vibration test provides useful information for 100% quality control of products before packaging. In the appliance manufacturing sector vibration testing for on-line quality control is increasingly important. Laser Doppler Vibrometry (LDV) has been already used to perform such tests on-line and it has become an established measurement technique.
In modern manufacturing industry flexibility and adaptability are key factors for the improvement of efficiency of production processes; both process control and product quality control depend on the availability of reliable information, and therefore on the quality of the data measured. For its non-contact nature and for its metrologic performance, laser vibrometry plays a more and more important and crucial role. This technique allows to realize flexible measurement systems that can implement adaptive and modular algorithms, comprising a large number of ready to use tools. In this thesis we will describe how it is possible to improve the performance of such systems by implementing self-adaptation and reconfigurability behaviors of the laser vibrometer aimed to reduce measurement uncertainty. Such behaviors are achieved by adding scanning mirrors and a dedicated camera, thus realizing a scanning LDV, which can displace the measurement beam at different locations. Self-adaptation (local adaptation) consists in the following behaviors:

the system aims at the desired target point over the washing machine (WM) by displacing the laser beam so to compensate effects of WM mis-positioning due to production line inaccuracies. After this preliminary phase, the automatic search for sufficiently large Doppler signal starts. The system searches for an optimal optical signal by slightly displacing the laser beam in the surrounding of the desired target point thus optimizing measurement uncertainty.
The system can support also reconfigurability (global adaptation), which consists in the possibility to plug-in/plug-out different post-processing algorithms for a deeper analysis of vibrations. For different production scenarios different diagnostic algorithms are chosen. This modular approach allows to consider the scenario of the production line and the quality of the operations carried out on the production line before the end product is made. In order to successfully use the self adaptation behavior to increase measurement accuracy, for this thesis a deep research of the causes correlated to uncertainty in industrial diagnostic has been made. It this work it is shown how the RMS amplitude of the Doppler signal (signal quality - SQ) is strictly correlated to measurement uncertainty, when SQ decreases then uncertainty affects the vibration velocity signal. Experimental data allow to say that SQ value is correlated to the morphology of the target surface and for a short period of time (10-15 s), so during the vibration the SQ value depends only on X-Y position of the laser beam on the target surface. These facts allow to use the SQ function as a cost function and the decrease the measurement uncertainty is a problem correlated to the optimization of the SQ value during the vibration measurements. The optimization strategy for the measurement enhancement achieved by the down-hill algorithm (Nelder-Mead algorithm) and its effect on signal quality (SQ) improvement are discussed.
With these features, this system is designed as a Quality Control Agent (QCA) and it is part of a Multi Agent System (MAS) that supervises all the production line. This thesis also shows the data exchange between the measurement system and other agents in order to realize a decentralized manufacturing system. In fact, in a distributed system, the estimation of the confidence level of the information provided by other agents plays an important role. The QCA associated to the measurement system has to be able to understand the confidence level of the diagnostic results provided. To understand the confidence level of the diagnostic information extracted from a feature, an uncertainty estimate model applied to a vibration signal acquired from a washing machine has been conceived and implemented.
In this way, the QCA can provide the overall diagnosis for the WM and estimate the uncertainty level with which the diagnosis has been performed. These information are used by the independent meta agent (IMA) to perform a trend analysis and elaborate suggestions and warnings to improve the process and product execution.

Keywords. Laser, vibrometry, industrial diagnostic, machine fault diagnosis, production line, optimization, adaptation, agent, multi-agent system, MAS, vibration, Nelder Mead, Downhill, algorithm, speckle noise, distributed intelligence.

1 Objective of this thesis and the GRACE project

The objective of this thesis is the development of a vibration based diagnostic system which exhibits autonomous behaviors aimed to manage, and possibly minimize, measurement uncertainty. This will allow to improve confidence level on the diagnostic output of the test station. The developments presented in the thesis are intended to be used for an on-line diagnostic station and the system will be designed to test appliances at the end of a production line. The system is based on a scanning laser Doppler vibrometer, equipped with a camera and scanning mirrors, designed to be able to:

- reposition the laser beam at the specific desired location on the target object, thus compensating possible positioning errors of the transport line;
- search for the maximum optical signal by slightly displacing the laser beam on the target surface, thus reducing the noise associated with speckle effects.

Such a behavior constitutes a kind of self-adaptation and self-optimization of system parameters (laser position on the target), which can be effectively implemented to improve the measurement system performance in terms of uncertainty. The system is then conceived as an agent, that is an entity which exhibits autonomy and capacity of interactions within a multi-agent system. The developments realized within this thesis are part of the activities of the GRACE project. The name GRACE is the acronym of inteGration of pRocess and quality Control using multi-agEnt technology, which is the name of a EU project in the field of materials and new production technologies funded under the seventh framework programme. As introduced before, the main objective of the GRACE project [1, 2] is to build an adaptive control system for responsive factories based on a cooperative multi agent system (MAS) operating at all stages of a manufacturing system, integrating process control with quality control, to develop a self-adaptive procedure into control and diagnostic systems at local and global level. This research activity aims to realize a quality control station for vibration functional tests for household appliance assembly line. The production line concerned is situated in the Whirlpool factory in Naples and at the end of the project a prototype will be installed on the line. The prototype will perform diagnostic analysis on the washing unit of the appliance during the functional test and it will be a part of the overall GRACE system. With the GRACE point of view, the vibration station, just mentioned in the previous paragraph, is correlated to a specific quality control agent (QCA) for a global adaptation procedure. For the QCA, the adaptation of parameters is employed to denote on-line procedures carried out during normal functioning of the production line, in order to iteratively approach the optimal configuration of the measurement system, which strongly depends on the specific measurement conditions, so to manage measurement uncertainty.
In practice, after the application of these concepts, the QCS (vibration station)[3] could perform a local adaptation in order to decrease measurement uncertainty:

- adapts measurement parameters: the laser beam position is adapted in a narrow area, searching a point of high SQ following a specific optimization algorithm;
- acquires environment: signal quality from the vibrometer is acquired at the new target point;

- stopping criterion: three stopping criteria are considered for this adaptation process, namely: 1) set the maximum number of iterations acquired, 2) set a threshold for the SQ, and 3) search for asymptotic convergence to maximum SQ. The vibration station will select the right stopping criterion considering the desired measurement uncertainty and/or different constraints.

After the optimal vibration signal is acquired, it will be processed in the data processing step, in order to reduce signal noise, extract features and classify possible defects detected on the appliance. In parallel, the QCA [4] receives information on the execution of the products from the other agents, (i.e. if the assembly of each component is correctly performed), and uses these information to adapt (global adaptation) the parameters for fault diagnosis and features extraction. Each agent is associated with an XML file describing the particularities and skills/services of the station that it will represent, that is read when the agent is launched in order to load the agent profile with the correct parameters.
Once the processing or testing operation is performed, the data collected are analyzed and the results are sent to the other agent of the infrastructure in an XML file. The QCA also collects data directly from the product line by the QCS. These measurement raw data are stored in a production database (GraDaCo) and are used by the independent meta agent (IMA) to perform a trend analysis and elaborate suggestions and warnings to improve the process and product execution.

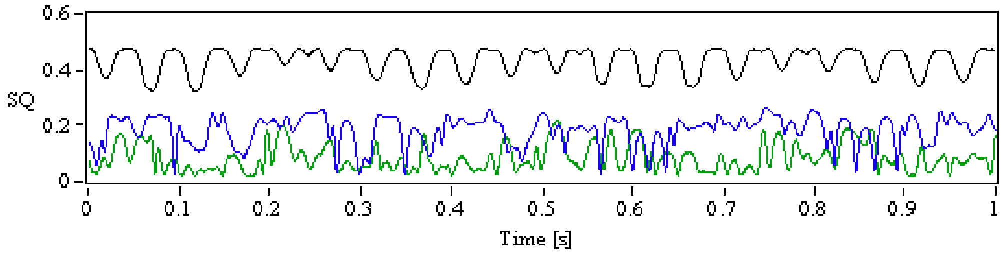
2 Light scattering, Doppler signal quality and drop-out noise

Literature on laser vibrometry deals in depth with the effect of light scattering on Doppler signal. Nowadays, commercial laser vibrometers are heterodyne Mach-Zender interferometers [5, 6, 7, 8]. They generate a frequency modulated signal, called the Doppler signal $\Delta I(t)$. If we neglect the low frequency terms, Equation 1 represents the Doppler signal;

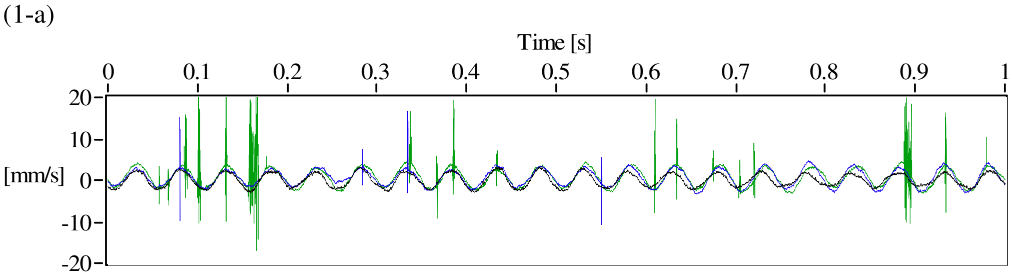
$$\Delta I(t) = I_{res}(t)\cos\left[\left(\omega_B \pm \omega_D\right)t + \Phi_{res}(t)\right] \quad (1)$$

It results from the interference at the photodetector of a reference beam shifted by the Bragg cell at the carrier angular frequency ω_B, and the target beam, whose frequency is shifted by $\omega_D(t)$ due to the Doppler effect at the scattering surface moving at velocity $v(t)$ in the direction of the target beam. If speckles move or evolve in time (see also [9, 10, 11, 12]), the resulting Doppler signal contains a time dependent amplitude $I_{res}(t)$ and a time dependent phase $\Phi_{res}(t)$: the existence of these two time dependent terms determines amplitude and phase modulation of the Doppler signal. When this happens two phenomena may occur [13]; if the Doppler signal amplitude remains sufficiently large for the demodulator to operate, then phase modulation produces speckle noise, while if Doppler signal amplitude drops to low levels and the demodulation process fails, then signal drop-out occurs. Commercial laser Doppler vibrometers (LDVs) allow to monitor the Doppler signal, in fact, more recent models output an analog DC signal derived from the original Doppler signal. In this thesis we will call “signal quality” SQ(t) the ratio of the logarithmic amplification of the RMS of the optical beat signal to its maximum value, SQ can therefore vary between 0 and 1.
Figure 1 shows a simultaneous acquisition of signal quality SQ(t), vibration velocity v(t) and vibration frequency spectrum FFT(f). Signal acquisition was made on the cabinet of a

washing machine during centrifuge; a total time of 1 s is acquired at 10kHz sampling frequency. The experiment intends to show the effect of different mean signal quality on the vibration signal. In particular each figure reports three traces in different colors: in black an acquisition with signal quality SQ having mean value around 0.5 is reported, in blue an acquisition with mean SQ about 0.2, in green with mean SQ lower than 0.1. Such different values of SQ may be obtained by slightly defocusing the LDV or by slightly displacing the laser beam by a fraction of a millimetre on the vibrating surface.
Figure 1-a reports the time recordings of SQ(t); it is interesting to observe that when mean SQ is large the signal appears almost periodic with a period equal to the rotation period of the drum of the washing machine; this confirms that SQ(t) varies because of rotation and translation of the vibrating surface. When SQ mean value decreases its time dependence is less organized. Figure 1-b shows the vibration velocity v(t) acquired in the three conditions; no signal drop-out occurs when SQ mean value is about 0.5, while some spikes of small amplitude occur when SQ decreases to 0.2 and a large number of drop-out spikes dominate the vibration signal when SQ is lower than 0.1. Drop-out noise occurrence therefore is correlated to the quantity SQ. Figure 1-c shows the growth of the noise floor on the spectrum computed from the vibration signal. In particular we can see that the presence of drop-out on the time signal determines an increase in broad band noise, which tends to mask out the vibration spectrum.



(1-a)



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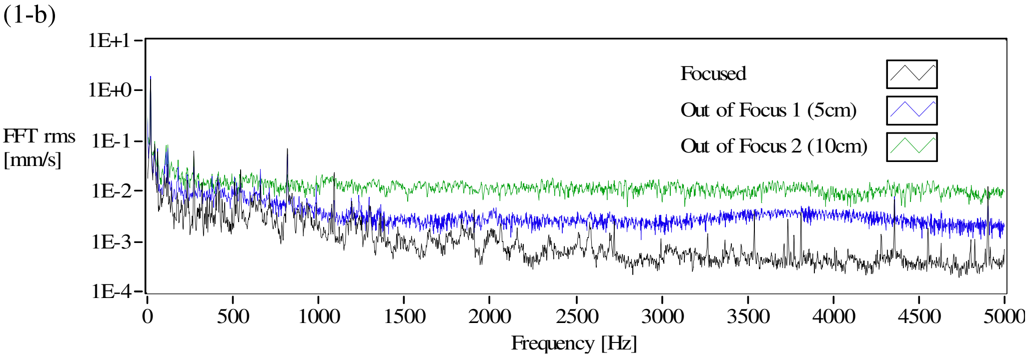

(1-c)

Figure 1 : a) Signal quality SQ(t); b) vibration velocity v(t); c) vibration spectrum

The analysis of data presented let us conclude that in order to reduce signal drop-out the signal quality SQ should be as large as possible and stable in time or only fluctuating slowly and with small amplitude. In practice we can conclude that if measurements are conducted with high values of SQ there will be a large chance that vibration velocity will be noisy, while in the case of low values of SQ vibration data will be affected by much lower noise, therefore significantly improving uncertainty of the measurement and the following diagnostic. This suggests that a proper positioning of the laser, in order to achieve an higher value of SQ, it allows a better measurement uncertainty. In order to achieve this goal it is important to look into the spatial dependence of SQ.

2.1 Spatial distribution of SQ

Several analysis of the spatial distribution of SQ in a small region over a non-vibrating enamelled surface has be done; the experiments are done with an LDV equipped with scanning mirrors. The LDV is scanned with a fine spatial resolution (0.023 mm) over a square matrix surrounding the hypothetical measurement point; the matrix has a 1.6 mm side length. The LDV is positioned at 740 mm from the surface, in a configuration similar to what can be met in an industrial application. Figure 2 shows a sequence of 4 maps of SQ observed after a horizontal translation with a step 0.3 mm from right to left. We can see that the spatial distribution of SQ remains correlated during translation, i.e. the structure translates keeping its main characteristics; it also evolves, but for a displacement of 0.3 mm this effect does not change the spatial distribution significantly. A lateral displacement of this order of magnitude or smaller is likely to happen during a vibration measurement on an appliance cabinet. Figure 3 shows a sequence of 4 maps of SQ observed after an in-plane counter-clockwise rotation with step 2° around an axis orthogonal to the surface. We again see that SQ spatial distribution rotates with some evolution, but mainly keeping its structure well recognizable; the map rotates with minor changes in morphology of SQ distribution. Figure 4 shows a sequence of 4 maps of SQ observed after an out-of-plane surface rotation around an axis laying in the plane of the surface with 0.2° step. The SQ spatial distribution appears to translate horizontally from left to right, as expected considering that it results from the scattering of light from the rotating surface, while slowly evolving in morphology. Rotations in the order of 0.2° can be met on appliance cabinets during vibration. All the spatial maps of SQ presented in the next page allow to say that, during vibration, the rotation and lateral displacement of the surface under the laser beam cause a fluctuation of SQ. This fluctuation depends on the spatial patterns of SQ. These facts led to a strategy for decreases measurement uncertainty. In order to meet the requirements on SQ, it is possible to move the laser beam within a small area surrounding the initial measurement point and look for an optimal SQ. This search can be done according to the following criteria:

- maximize mean signal quality SQ, if SQ on the initial point is not large enough.
- keep SQ as stable as possible.

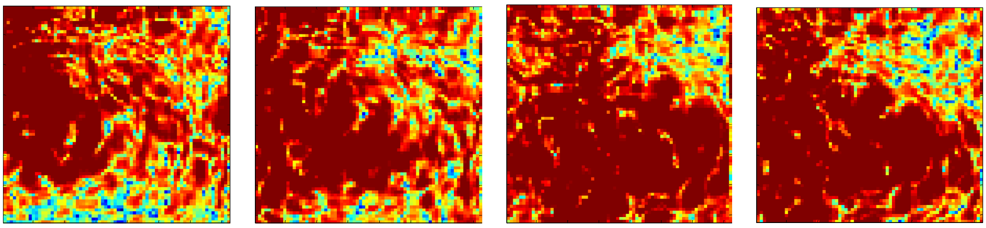

Figure 2 : Sequence of spatial distribution maps of SQ over a matrix of 1.6 x 1.6 mm² on the same static surface after horizontal displacement (0.3 mm steps from left to right).

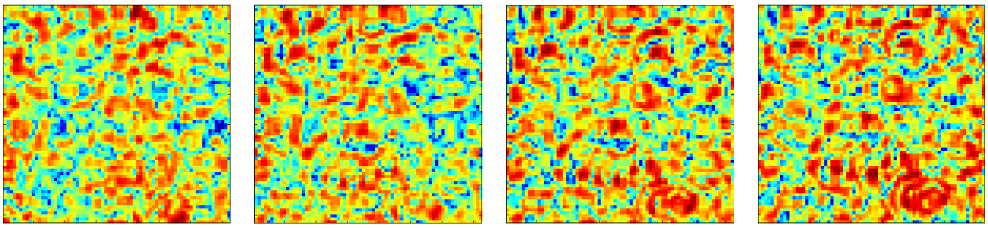

Figure 3 : Sequence of spatial distribution maps of SQ over a matrix of 1.6 x 1.6 mm² on the same static surface after in-plane counter-clockwise rotation around an axis orthogonal to the surface (2° steps).

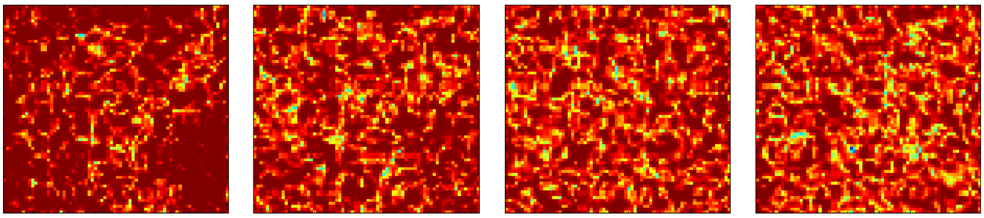

Figure 4 : Sequence of spatial distribution maps of SQ over a matrix of 1.6 x 1.6 mm² on the same static surface after out-of-plane rotation around a vertical axis laying on the surface (0.2° steps).

While the first criterion was already considered in previous literature, the second criterion was not, to our knowledge; mainly because this problem is not significant on diffuse scattering surfaces which are normally dealt with in mechanics. The fulfilment of the first condition implies a search for a maximum of SQ amplitude, while the second implies the analysis of SQ fluctuations. This can be done by analysing SQ in time or frequency or more simply by computing the standard deviation of a sequence of SQ data with respect to its mean value. This strategy should be implemented to reduce uncertainty of a diagnostic system for appliances working with an LDV measuring on enamelled metal sheet in order to reduce drop-out noise to a manageable limit. In the next page, Figure 5 shows a flow chart of such an implementation. Of course, when changing the measurement point P(i,j) we should consider that vibration velocity changes from point to point. This change should have a negligible effect on the diagnosis of vibration. Such a condition can be fulfilled if the change in amplitude of vibration velocity falls within the natural scatter of vibration velocities of appliances that are being tested. In order to estimate this change due to measuring in a different point we should know the operational deflection shapes of the appliance under test. Previous experience (see for example[14, 15, 16, 17, 18, 19, 20, 21, 22]) shows that on the cabinet surface of a washing machine a displacement of less than 0.5 mm of the measurement point will produce a negligible error in the estimate of the local vibration velocity in the typical frequency range where vibrations are measured on the cabinet (typically 0-3 kHz)[23].

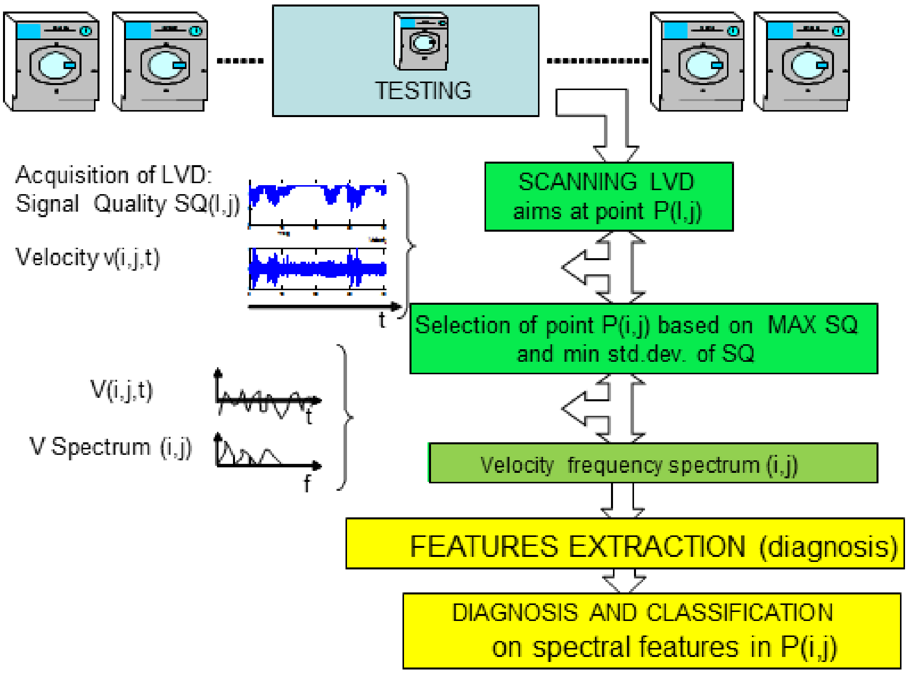

Figure 5 : Strategy to improve measurement uncertainty.

3 Self-adaptive laser vibrometry for on-line diagnostic

3.1 Description of self- adaptation mechanisms

As already outlined in the introduction, a self-adaptive laser vibrometer accomplishes two tasks: a) it is able to automatically identify and point at the desired measurement location and b) it is able to maximize Doppler signal level at that location. The whole sequence of steps that the system performs to have such a behavior are described in the block diagram of Figure 6 [24], the system performs the following adaptation steps:

1. acquire environment:
   a) the laser beam position is acquired at the start of the test,
   b) signal quality from the vibrometer is acquired at the desired target point;
2. adaptation:
   a) the laser beam is repositioned at the desired target point by using image analysis;
   b) the laser beam position is adapted in a sub-millimetric narrow area surrounding the target point, searching for a point of high SQ following a specific optimization algorithm;
3. stopping criteria: if signal quality is above a fixed threshold the vibration velocity is acquired and the measurement is performed.

The adaptive behavior implemented in the self-adaptive LDV system is outlined in the flow chart which describes its behavior (Figure 7).
This behavior of the self-adaptive LDV system is implemented into the quality control station(QCS), which has associated a Quality Control Agent (QCA) and they are part of the Multi Agent System (MAS) that supervises all the production line. The QCS behavior is

therefore defined so to perform the automatic search for the desired measurement point, so to compensate transport system inaccuracies, and a minimization of measurement uncertainty during the on line tests, so to maximize the confidence level on the diagnosis performed by the system. The behavior performed by QCS is called local adaptation in order to distinguish between the global adaptation or system reconfigurability performed by QCA. This chapter does not discuss system reconfigurability (global adaptation), while it focuses on system local self-adaptation, which is presented in the following paragraphs.
The global adaptation behaviour will be discussed in chapter 4 where the communication between QCS e QCS will be explained.

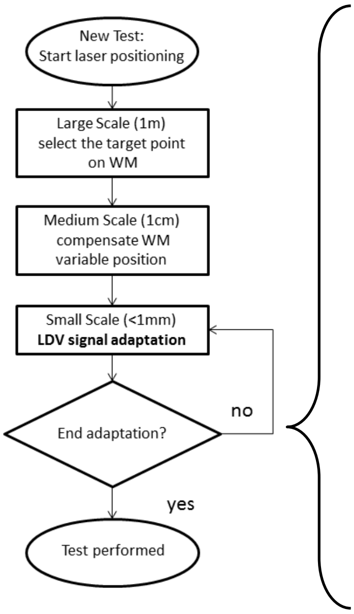

Figure 6 : Laser beam adaptation.

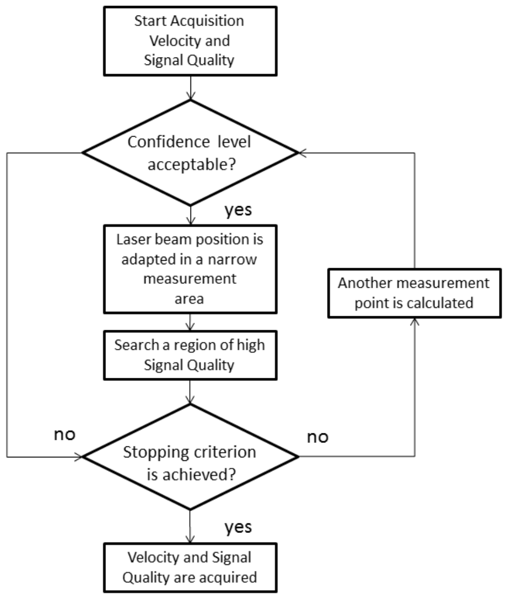

Figure 7 : LDV signal adaptation.

The first kind of self-adaptation performed by the self-adaptive LDV is the re-positioning of laser beam at the desired measurement set point. This is done by a feed-back loop based on the information provided by the image of the laser beam on the WU surface. The second kind of self-adaptation is performed at a microscopic scale by slightly displacing the laser beam in a narrow region around the desired set-point, in order to increase the amplitude of the optical signal of the vibrometer. As shown for the spatial distribution of SQ when a vibration test is taken on a machine which has just stopped at the QC station, the laser beam may randomly fall on a region of large or low SQ. When this second situation happens, the test will be performed with large noise, therefore with large uncertainty.
Given these considerations, in order to reduce measurement uncertainty one should control laser beam position at a sub-millimeter scale and search for the largest SQ possible in the vicinity of the target measurement point. This is a self-adaptation process that can be based on the optimization of the SQ over x and y; SQ plays the role of the objective function of the optimization algorithm. The optimization algorithm was selected to be reliable, stable, well-known, easy to be implemented and computationally not intensive: we are using the Nelder-Mead simplex method [25], also called Downhill algorithm. This algorithm consists in finding the minimum of the function SQ(x,y) using simplexes (in 2D they are triangles). From a starting point, arbitrary defined by the current laser beam and WU position, the algorithm generates a new simplex thorough basic operations such as reflections, expansions and contractions. During the optimization process, the size of the simplex

tends to decrease, so that the finest definition of the function maximum is obtained. This specific implementation of the down-hill algorithm drives the sequence of sub-millimetric displacements of the laser beam. In Figure 8 the series of positions that the laser beam takes during the search for maximum SQ is reported. Some criteria for stopping the self-adaptation process are needed. We have implemented the following options:

1. the process is stopped after SQ has reached convergence to a maximum;
2. the process is stopped once SQ has overcome a fixed threshold;
3. the process is stopped after a fixed number of iterations, independently of the SQ value reached.

The first option would bring to the best SQ, but requires an undefined number of iterations, i.e. of time. The second guarantees to have SQ at the desired level, but again it may require an indefinite time, but probably shorter than option 1. The last option operates at fixed tie and may provide an unpredictable SQ increment. The choice therefore will depend on the scenario of the application being dealt with.

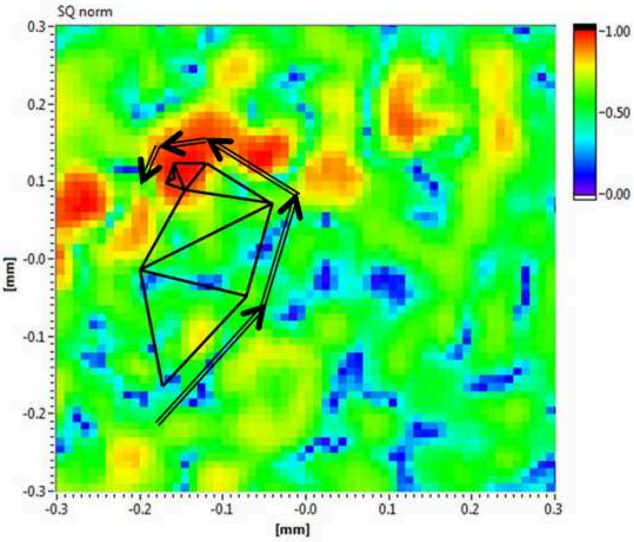

Figure 8 : Laser position sequence shown by arrows: SQ is maximum at the end of the adaptation process.

3.2 Results of the application of the self adaptive laser vibrometry

The effectiveness of the self-adaptation of laser beam position for maximizing SQ has been tested through a series of experiments that try to simulate what happens in the production line during a rather long period, when different items, in our case washing machines, arrive in the testing station in front of the vibrometer. Results are always showing large increments of SQ, often larger than 100%. This means that uncertainty in the vibrations measured can be improved considerably if the self-adaption procedure is implemented before each test. This for quality control applications means a significant step to increase confidence level of the diagnostic output. The positive effect on signal to noise ratio is even more remarkable when observed in the frequency domain; Figure 9 shows two spectra of the vibration measure without and with the self-adaptive procedure which optimizes SQ. When the adaptation process is active the spectra measured manifest a significant improvement of the signal-to-noise ratio from 63.6 dB to 88.6 dB obtained with self adaptation is on.

If at one point, due to low SQ and large noise, it was impossible to observe many spectral lines, soon after applying the self-adaptive procedure the noise level decreases and the spectral content emerges from the noise floor and can be correctly observed.
Such an increase in signal-to-noise ratio will determine a larger confidence level in the diagnostic output from a quality control station which implements a self-adaptive laser vibrometer. Once this behavior is implemented together with the automatic search for the desired measurement point described before, the quality control system exhibits self-adaptive behaviors that allow to implement it as an agent, in particular a QCA, and have it operating on a multi-agent system in charge of production factory control.

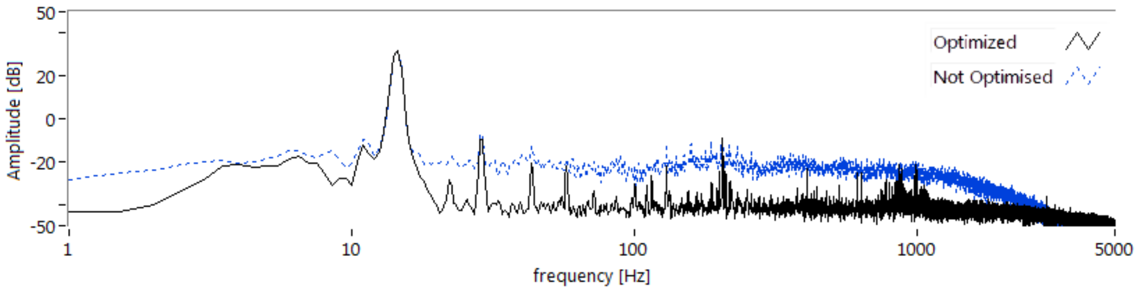

Figure 9 : Effect of vibration spectrum of the self-adaptation procedure.

4 The Quality Control Station on production line

The vibration signals acquired from the QCS are analyzed using different standard algorithm in time and frequency domain [26]. In Figure 10 the highest peak of the spectrum is relative to the frequency rotation of the drum of the washing machine f_{drum} = 22.1 Hz (1326 rpm). The frequency relative to the motor is: f_{motor} = 278 Hz (16680 rpm), that is the same value predictable using the transmission rate of the washing machine.
Using the mechanical features of the washing machine, as previously described, it is possible to compute the belt pass frequency, f_{belt} = 16.8 Hz. As expected this spectral line is situated before the drum frequency. This project is not aimed at developing new feature extraction methods; rather its aim is to use state of techniques and apply them to washing machine diagnostics, within a multi-agent system of which the vibration test station is part, and particular attention has been devoted to self-adaptation algorithms in order to minimize the measurement uncertainty during the on line production test.

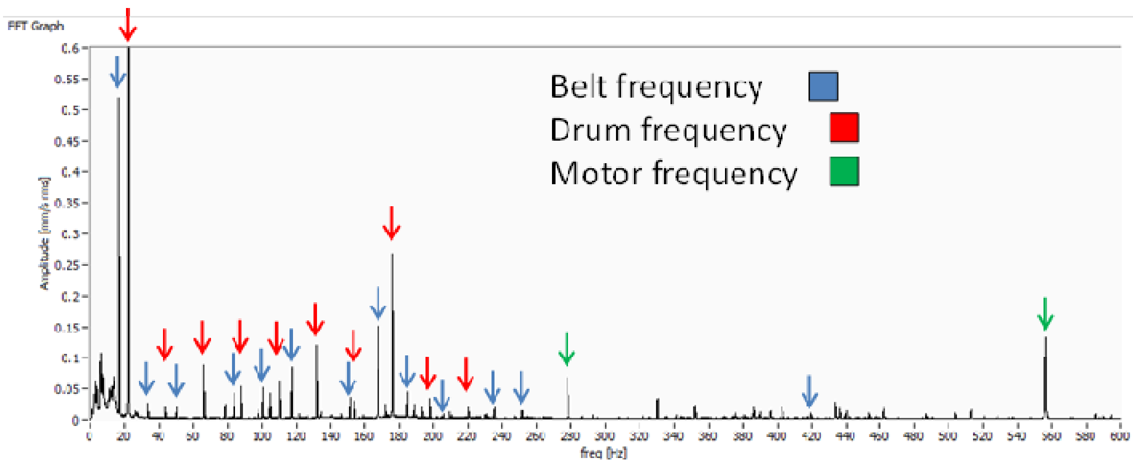

Figure 10 : Some characteristic lines identified on a vibration spectrum; f_{belt} = 16.8 Hz, f_{drum} = 22.1 Hz, f_{motor} = 278 Hz.

4.1 Global adaptation, QCA and QCA

The quality control station (QCS) is associated to a quality control agent (QCA). This agent is part of the multi-agent system (MAS) infrastructure and it is responsible for managing the operations performed by the control station. All the agents of the production line are connected with the MAS, so at any moment it is possible to know the situation of the production line: for example it is possible to know if there were problems during the assembly of the washing machine which is now under XML file, in test. The QCA and the QCS interact with each other by exchanging information with a this way the QCS is able to apply the suggestions elaborated from the QCA on the basis of the information collected in the MAS. The GRACE project does not aim to develop new diagnostic algorithms, but to implement the existing ones in an innovative fashion within a multi-agent system. In particular the set of characteristic features can be used in a modular way; by modular feature extraction we intend that, depending on the scenario, the feature extraction may vary. This means that the diagnostic recipe will change according to the scenario that is taking place. The diagram in Figure 11 depicts the concept, which means that the diagnostic process adapts to the situation. In Figure 11 the blue arrows are referred to the actions performed by the QCA for the activation of the global adaptation. The QCA interacts with the production system through the MAS, which provides information on the production scenario, such as actual production rate, cycle time, quality expected. Within the QCA the signal quality from the QCS and the following uncertainty, or confidence level, are monitored. If the confidence level of the diagnosis is acceptable for the given scenario, then the QCS outputs the diagnosis and its confidence level. Otherwise, the QCA outputs the request to improve either the measurement or the processing (for example it may require to increase the averaging so to reduce influence of random noise).

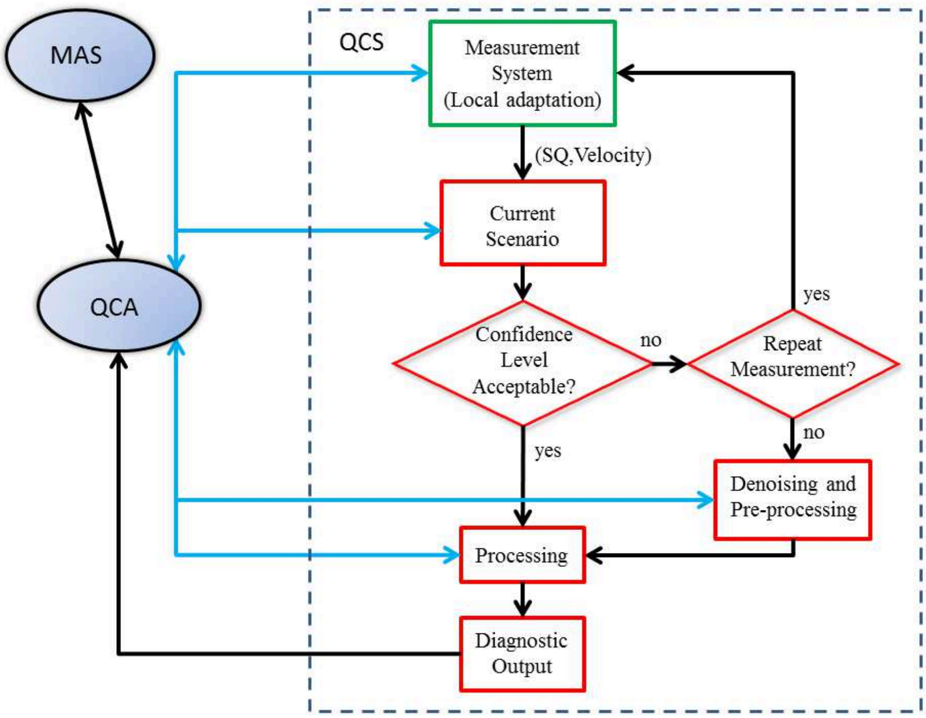

Figure 11 : Scheme of the global adaptation in signal processing

Figure 12 shows the auto cycle procedure for the vibration test. In Figure 12, the numbered arrows are referred to the actions performed by the QCA during the vibration test, the green box is referred to the local adaptation discussed in chapter 3, and the yellow one is referred to the global adaptation, which is described in this chapter. At the beginning the WM under test is loaded on the functional test bay. The QCA reads the model (12NC) and the serial number of the washing machine from the production line. These information (arrow number 1 in Figure 12) are used to modify the test plan (arrow number 2) and to apply the product scenario (arrow 3) understood form the IMA, for the WM currently under test. The WM starts the centrifuge and the run up is acquired. During the steady state the local adaptation is performed by the QCS using the parameters provided by the QCA and the value achieved for the SQ is sent to the QCA (arrow number 4 in Figure 12). The QCA develops the product scenario on the basis of the information received from the IMA and uses the SQ from the QCS to select the right diagnostic algorithms for features extraction (arrow number 5), the classification is done and the results are sent to QCA and IMA (arrow number 6). This is what happens every time a WM it is tested on the production line.

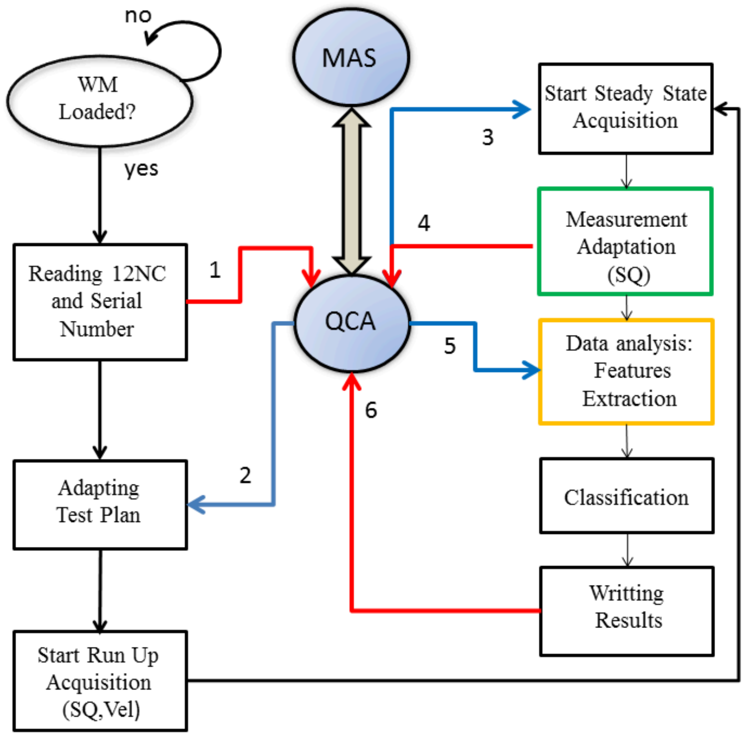

Figure 12 : Auto cycle diagnostic test.

5 Measurement uncertainty

At the end of an auto cycle test, the fault diagnosis is performed for each WM. The values of the features computed are stored and these data are analyzed in order to quantify the overall quality of the production line. With these information the IMA is able to understand what action should be taken to increase the quality or the velocity of the production line. Therefore for a correct analysis the IMA needs correct information, or at least, the possibility to separate the reliable information from the misleading ones. The confidence level of the information provided by QCA is related to the uncertainty of the features extraction process which depends on the SQ level achieved during the vibration velocity acquisition. In fact, as shown in chapter 2, the drop out noise is strictly correlated to the SQ level: the higher the SQ level, the higher the signal to noise ratio. Otherwise, when SQ decays the drop out spikes superimpose to the vibration signal and those spikes cause a pseudorandom noise, which is the superposition of random broad band noise and noise components at the same frequency of the vibration being observed. This problem increases measurement uncertainty. To understand the confidence level of the diagnostic information extracted from a feature an uncertainty estimate model applied to a vibration signal acquired from a washing machine could be used. This operation allows to understand the trend of the uncertainty versus SQ for a specific third octave band center frequency. For a 10^{th} order polynomial the R value of the uncertainty estimate model is 0.943, it means that the fit obtained by the model explains 94.3% of the total variation in the data about the average. Hereafter the trend of uncertainty amplitude versus frequency at constant values of SQ is presented (Figure 13). As it is shown, the uncertainty model could be used to estimate and predict the uncertainty of a feature by knowing its frequency value and the SQ value of the vibration signal (Figure 14).

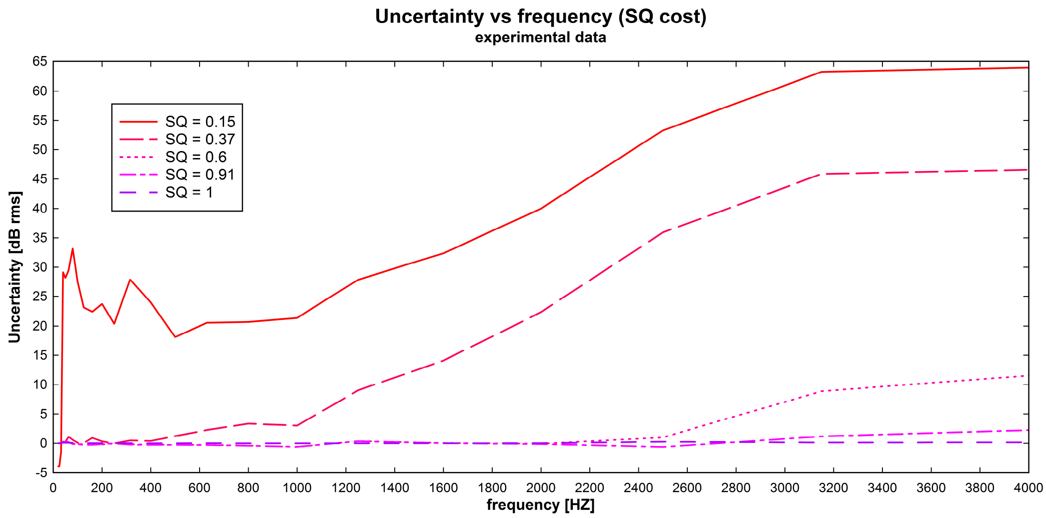

Figure 13 : Uncertainty amplitude [dB RMS] versus frequency for experimental data, each curve is obtained for a fixed SQ value.

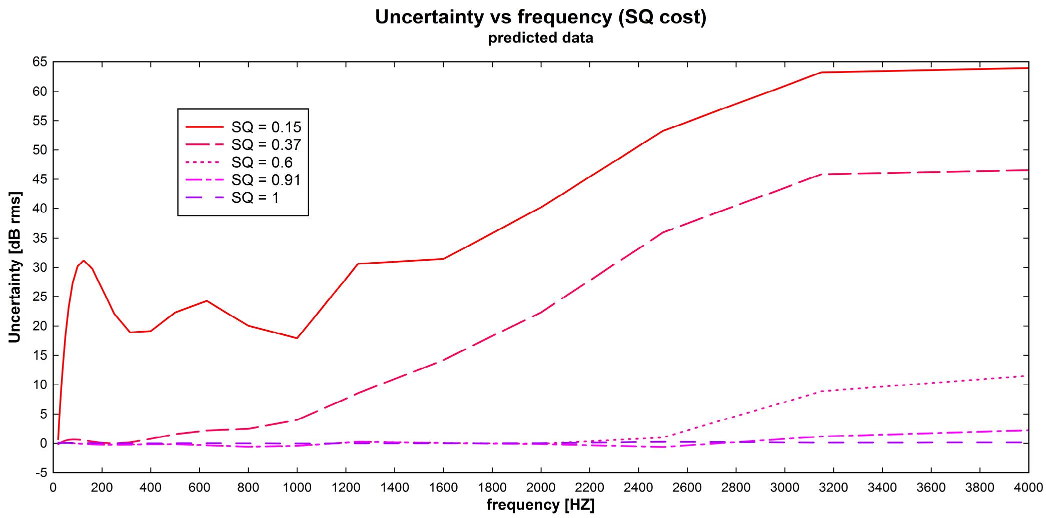

Figure 14 : Uncertainty amplitude [dB RMS] versus frequency for predicted data, each curve is obtained for a fixed SQ value.

6 Conclusion

This thesis deals with the realization and the application of Laser Doppler Vibromety (LDV) in modern manufacturing systems. In order to improve the efficiency of the production process, a reliable information excanghed obtained from a flexible and adaptable quality control station (QCS) is needed. Such QCS uses the multi-agent-system (MAS) to provide and exchange information so as to improve the process and product execution. A QCS based on LDV with agent behaviors has been realized with the purpose to increase the efficiency of the Whirlpool washing machines production line in the factory in Naples. This QCS is able to perform a local adaptation in order to decrease the measurement uncertainty from the vibration signal acquired on the washing unit (WU) of the washing machine (WM) on the production line. This local adaptation is realized by applying an optimization strategy to the laser Doppler signal amplitude (SQ) of the vibration velocity signal during the on line tests. The quality control station (QCS) is associated to a quality control agent (QCA). This agent is part of a multi-agent system (MAS) infrastructure and it is responsible for managing the operations performed by the control station. The QCS uses well known algorithms applied to fault diagnosis but in an innovative fashion within a multi-agent system. The QCA interacts with the production system through the MAS, which provides information on the production scenario, such as actual production rate, cycle time, quality expected. Within the QCA, the SQ from the QCS and the following uncertainty, or confidence level, are monitored. QCA selects the more useful diagnostic algorithm in order to perform a correct diagnosis without wasting time: deep analysis are not performed when they are not needed. The information provided by QCA are used by intelligent meta agent (IMA) to understand what action should be taken to increase the quality or the velocity of the production line. Therefore to perform a correct analysis the IMA needs correct information, or at least, the possibility to separate the reliable information from the misleading ones. To understand the confidence level of the diagnostic information extracted from a feature, an uncertainty estimate model applied to a vibration signal acquired from a washing machine was used. This uncertainty model and the data obtained from the local adaptation performance tests will be used to simulate the performance of the measurement system. With the self-adaptation procedure, the QCS is able to use the diagnostic information between 0-1600 Hz: this frequency band, in fact, contains useful diagnostic information. Further works will be done in order to optimize the uncertainty estimation model and to analyze the performance of the overall measurement system composed of QCA and QCS.

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