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Selective and validated data processing techniques for performance improvement of automatic lines

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Abstract. Optimization of the data processing techniques of accelerometers and force transducers allowed to get information about actions in order to improve the behavior of a cutting stage of a converting machinery for diapers production. In particular, different mechanical configurations have been studied and compared in order to reduce the solicitations due to the impacts between knives and anvil, to get clean and accurate cuts and to reduce wear of knives themselves. Reducing the uncertainty of measurements allowed to correctly individuate the best configuration for the pneumatic system that realize the coupling between anvil and knife. The size of pipes, the working pressure and the type of the fluid used in the coupling system have been examined. Experimental results obtained by means of acceleration and force measurements allowed to identify in a reproducible and coherent way the geometry of the pushing device and the working pressure range of the hydraulic fluid. The remarkable reduction of knife and anvil vibrations is expected to strongly reduce the wear of the cutting stage components.

Keywords: Film cutting, measurement, uncertainty, accelerometer, RMS, envelope

1 Introduction

In mechanical industry the requirements of increasing the product quality and the production rate ask for an optimization of many aspects concerning the design of components of the production line and the control of the production process.

Among many examples, an interesting application refers to nonwoven textile industry: in fact, the increase of production rate and of product quality are requested for both economic and commercial reasons and with reference to traditional and emerging world markets together.

In this paper the attention is focused on converting machinery for diapers production, for both technical complexity of the production line and its economic relevance if it is considered on the whole. In fact, production and environmental issues have to be faced for worldwide competiveness improvement. In particular, a continuous and remarkable production rate increase is required to production lines of very high mechanical complexity and raw material and energy consumption should be strongly reduced. That objectives require continuous and diffused improvement actions.

Among many aspects, the cutting of pieces of materials to be assembled is a fundamental operating step of the manufacturing process [1–3]. In fact, a clean and accurate cut allows us to realize diapers which are geometrically and esthetically appreciable [4, 5]; on the other hand, a cut correctly operated from a mechanical point of view, with reference to both the contact forces between knife and anvil and the relative motion between them, is able to cooperate to a good cutting action reducing the wear of knives and the production of fibers. These actions allow us to improve the stability of performances during the time, with reduced maintenance actions and cost [6].

If the cutting operation is studied, many aspects have to be taken into account, concerning the characteristics of the film or nonwoven web, the coupling conditions existing between knife and anvil, the relative peripheral slip between the cylinder carrying the knives and the anvil cylinder. The most studied aspects are the contact force control, the kinematic radial coupling of knife and anvil, and the dynamic behavior of the mechanical components during the cutting, monitored by accelerometers [7–9]. There are also examples of cutting tools specifically realized and instrumented to monitor the cutting process for both quality of product and wear of the cutting tool improvement [10, 11]. The described experimental set-up allowed to get experimental information on cutting mechanism, depending on geometry of the webs [10], and on geometrical and thermal parameters useful for condition monitoring [11]: anyway, the proposed configurations seem

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to need a further development for reliable implementation on the production line.

Reduction of peripheral slip between the surfaces of knife and anvil cylinder in the cutting stage of a high speed, high quality production line of diapers has been described in a previous work of authors [12]: a tailored monitoring system of the slip allowed us to optimize process parameter for peripheral sleep reduction.

Simply and accurately monitoring the mechanical coupling conditions of knife and anvil will be useful with reference to many aspects: simple methods to design the actuating system of the coupling force are available, on line monitoring of the coupling conditions also in real production lines could be set, the definition of the process parameters in order to optimize the duration of the involved mechanical components and to reduce the maintenance costs could be carried on.

These goals require that the measurement techniques are simple, reliable, accurate and selective, in order to give differential information about the effect of all the parameters to be set up and/or measured for both design and monitoring purposes.

According to these requirements more measurement techniques should be analyzed, being robust, consolidated and simple, useful for this study but also transferable to the line; simple, selective and reliable data processing techniques have to be implemented; validation of measurements, to be intended as reproducibility of them by means of inter-comparison of data of different sensors, is a further requirement to be satisfied.

Based on these considerations, in this paper vibration, driving current and force measurements will be analyzed, to get information about design of the actuating device, with reference to the length of pipes, to the fluid to be used in the hydraulic circuit, to the pressure of exercise of the actuating system, in both static and dynamic working conditions.

According to the above requirements, the most suitable technique to detect the effects of changing the above elements will be chosen, also taking into account consolidated literature suggestions.

In order to evaluate the classification ability of each data processing technique, accuracy and repeatability of measurements will be examined, as possible performance indicators for both design optimization and condition monitoring implementing.

2 Materials and methodology

The real configuration of a cutting system of a converting machinery for diapers production has been replicated in a laboratory test bench.

The test bench includes a revolving knife and an anvil, where the former is constituted by a cylinder with sharp profiles (Fig. 1), and the latter consists of a non-driven roller supported in a lubricated slides cradle. The cradle exerts an elastic force against the cutting unit by a pneumatic system, whose pressure can be set as required (Fig. 2).

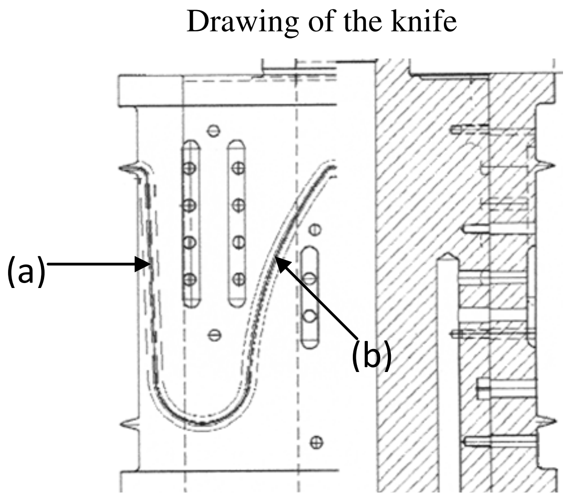

Fig. 1. Drawing of the knife. The sharp profiles (a) and (b) produce the impacts on the anvil.

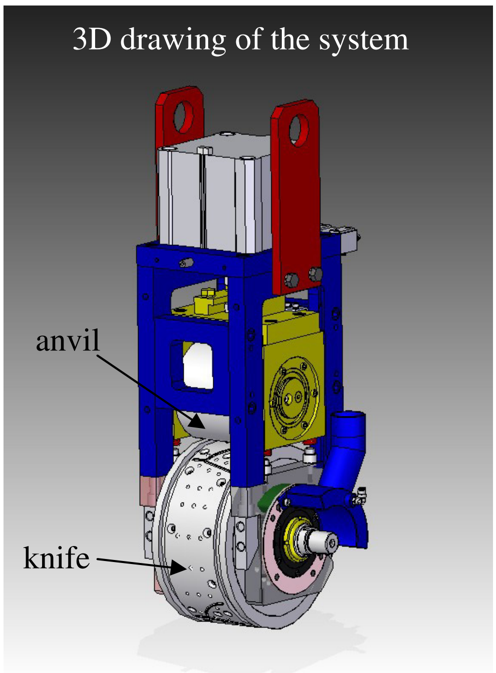

Fig. 2. 3D drawing of the knife-anvil system.

An accelerometer has been positioned vertically on the frame supporting the system, perpendicularly to the knife axis.

The accelerometer used is the Piezoelectric Charge Accelerometer BRUEL & KJAER, Series 4500.

A load cell GEFRAN, model AM KN 2D (full-scale 20 kN, sensitivity 1.987 mV/V), has been positioned between knife and anvil to measure the pushing force between them.

A Bourdon pressure gauge, precision class 0.25, full-scale 10 bar, has been used to set the working pressure of the pneumatic system.

For the acquisition a NI CompactRIO 9104 system, based on a FPGA (Field-Programmable Gate Array), has

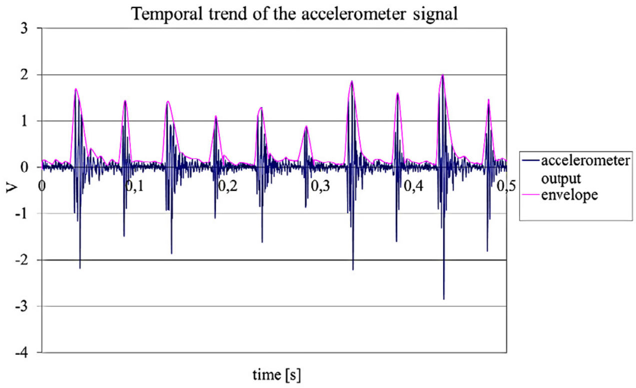

Fig. 3. Temporal trend of the accelerometer output signal and envelope.

been used, with the following input modules: NI 9215 for the accelerometers and the servomotor current signals, NI 9237 for the load cells signals, NI 9411 for the encoders signals.

The following instruments have also been used:

– Conditioning amplifier NEXUS, BRUEL & KJAER, Type 2693.
– Low pass filter Kemo VBF/23 for the prevention of aliasing.
– Conditioning module RX-SCC-503, Robotronix, with a current transducer (full-scale 50 A, output 10 V) for the acquisition of the servomotor current signal.

The overall bandwidth of the accelerometer system is of about 2.0 kHz.

The trend of the signal versus time (Fig. 3) clearly shows the phenomenon of the impact and the "rebound" of the sharp profiles of the knife on the anvil. The effect of these impacts and rebounds has to be reduced in order to make more and more regular the cutting of pieces and to reduce the wear of the sharp profiles themselves. Reducing the strength of the impact and the produced vibrations is expected to improve the quality of products and to increase the life time of knives.

The graph shows more intense impacts, alternated to others less intense, to be interpreted, taking into account the shape of the sharp edges of the knife (Fig. 1). In particular, the most intense impacts should be attributed to the cutting edges positioned almost in the direction of the knife axis (a) and the others should be attributed to the cutting edges forming an angle with respect to the knife axis (b), as shown in Figure 1.

The impact characteristics obviously depend on the solution the coupling between knife and anvil cylinders is realized.

In order to reduce the effects of impacts, some modified solutions have been compared, as suggested by a direct and validated experience in the designing of these stages:

1. a pneumatic system;
2. a hydraulic system with long connecting pipes and oil as a working fluid;
3. a compact hydraulic system (minimum length of pipes) and oil as a working fluid;
4. the same compact system described at the point 2, but working with water and glycol.

In all tests that have been carried out, the rotation speed of the knife has been set at 88 rpm, that is the real speed at which the system operates in the field.

Based on operator experience, the tests have been carried out in operating conditions, which are considered "normal" for most of the cutting stages, that is at a pressure ranging from 1 to 6 bar.

If the data processing techniques are considered, two methods have been examined to quantify the effect produced by the impact of the cutting edges on the anvil, in order to carry out a comparison of results:

– the root mean square (RMS) in the time domain of the accelerometer output signal, considering a time interval for the calculation corresponding to 10 revolutions of the knife;
– the fast fourier transform (FFT) of the envelope of the accelerometer output signal.

The RMS of accelerometer signal is a classical, simple and straightforward analysis method for the diagnostic of mechanical systems [13,14].

For a discrete number of values $x_1,\ x_2,\ldots,x_n$, the root mean square is calculated according to the following formula:

$$\mathrm{RMS} = \sqrt{\frac{x_1^2 + x_2^2 + \ldots + x_n^2}{n}}. \tag{1}$$

On the other hand, the analysis of envelopes is often used [15–17] for the analysis of impulsive signals, typically produced by shocks or localized defects of rotating parts, such as bearings.

In this case too, the monitoring is carried out with reference to periodical impacts of knives. Envelope analysis allows us to paid attention to the phenomenon under study, smoothing the effects of random variability among impacts due to peripheral velocity variation and random variability of impacts. Figure 3 shows the envelope of an output signal of the accelerometer.

If the Fourier transform of the envelope of the signal is calculated, the frequency peak related to vibrations due to the impacts of knives is well evident and located at a frequency little more than 10 Hz (Fig. 4). This frequency value depends on both the rotation frequency of the knife drum and on the number of knives set on the cylinder surface, being, respectively, 88 rpm and 7. The measured frequency exactly corresponds to the theoretical one.

The other peak (at a frequency of nearly 2.25 Hz) is, instead, correspondent to the anvil rotation frequency, which is equal to the knife rotation frequency (∼88 rpm = 1.5 Hz) multiplied by the ratio between the diameters of knife and anvil (∼235/150).

It Figure 4 the FFT spectrum of the signal related to the servomotor current connected to the knife is also shown. The principal peak related to the knife rotation

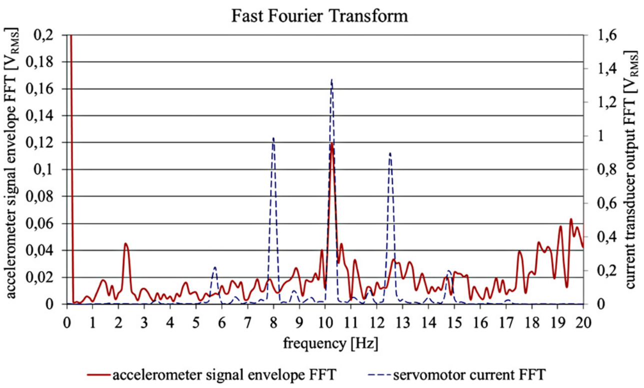

Fig. 4. FFT of the envelope of the accelerometer signal.

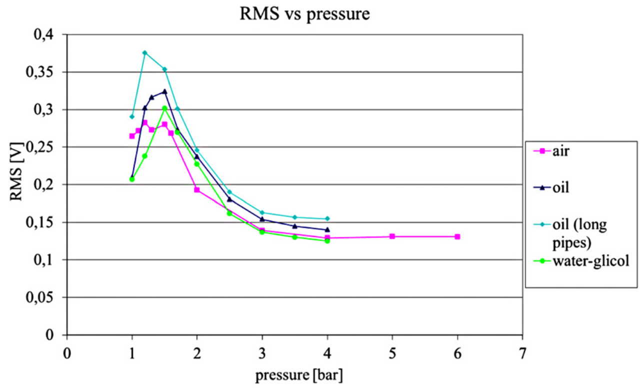

Fig. 5. RMS of the accelerometer output versus the pressure, in different configurations: compact pneumatic system, compact hydraulic system and oil as a working fluid, hydraulic system with long connecting pipes and oil as a working fluid, compact system with water and glycol.

is quite evident, while lateral peaks indicate the modulation action on the impact intensity by the circumferential defects of the anvil.

It is interesting to note that modulation action is absent in acceleration signal, which appears to decouple effects of knife and anvil from each other: due to this effect the acceleration signal will be used hereinafter.

Furthermore, these preliminary results show that both data processing techniques are able to supply reliable information and in a complementary way. The selected data processing techniques will be both used only with acceleration data.

Therefore, in the following paragraph, tests carried out on the experimental bench will be described, in order to compare different configurations, both for the fluid, both for the geometry. Moreover, the described different techniques for data analysis will be examined, and the results will be compared in order to detect differences in ability of discriminating differences among the tested solutions.

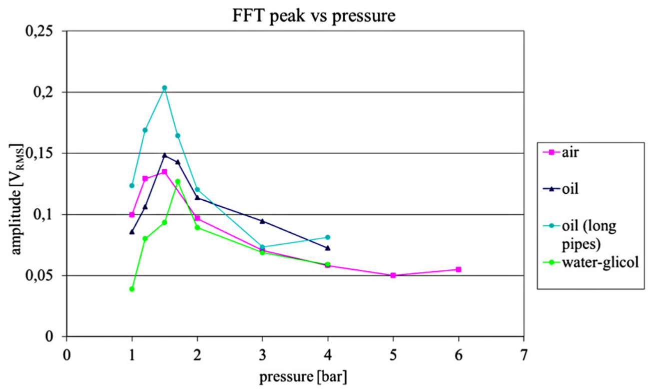

Fig. 6. Trend of the peaks of the envelope FFTs versus the operating pressure, in different configurations: compact pneumatic system, compact hydraulic system and oil as a working fluid, hydraulic system with long connecting pipes and oil as a working fluid, compact system with water and glycol.

3 Results

The analysis of the accelerometer signal has been carried on with reference to the above different configurations of the pushing system.

In Figure 5 the RMS of the accelerometer output is represented with reference to different pressures for all the described configurations. It can be noticed that, apart from the low pressure range, corresponding to pressures less than 1.5 bar, the trend of vibration intensity is decreasing with the pressure, since at higher pressures the rebound effect of the cutting edges on the anvil is reduced. Test results allowed to define the most suitable range of operating pressure of this specific cutting system, corresponding to the interval 2 to 3 bar. In fact, in all the considered configurations the phenomenon tends to stabilize at pressures greater than 3 bar.

Vibration measurement data of the same tests have been processed also by the envelope method for all the different configurations considered. The behavior of the peak amplitude of the envelope FFT has been plotted as a function of the working pressures (Fig. 6). By comparison of graphs of Figures 5 and 6, similar information is gained from the two methods, the RMS and the FFT of the envelope, if the influence of the working pressure is considered.

The main difference between the methods is related to the dispersion of results, and then to the uncertainty of methods, being greater in case of the envelope technique. As an example, Figure 7 shows a comparison between the results of both data processing techniques with reference to the hydraulic compact system. In the graphs the “error bars” represent the standard deviation of repeated tests. The reduced uncertainty of the RMS method allows to better discriminate between trends corresponding to different configurations and for that it will be considered in the following.

In order to optimize the behavior of the pushing system in the cutting stage, two aspects were considered, the former related to the length of pipes (long/compact),

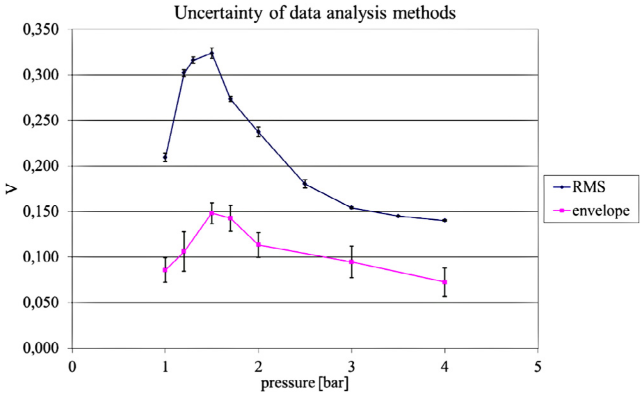

Fig. 7. Comparison between the RMS method and the envelope FFT method, with reference to the compact hydraulic system and oil as a working fluid.

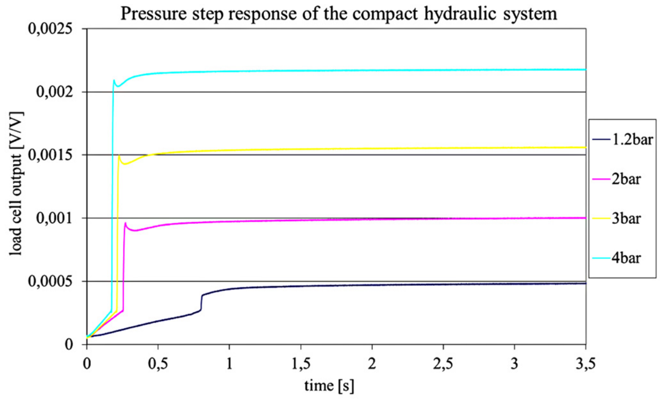

Fig. 9. Response at a pressure step of the compact hydraulic system.

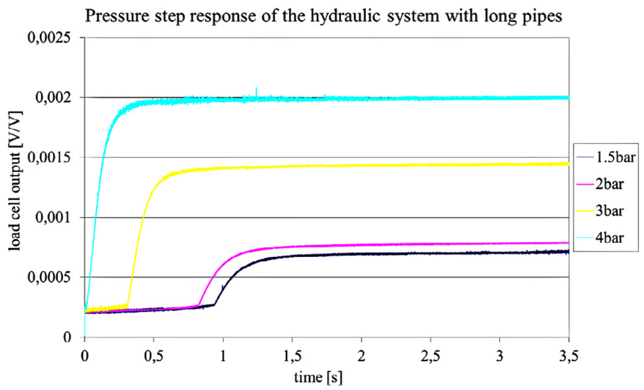

Fig. 8. Response at a pressure step of the hydraulic system, with long connecting tubes.

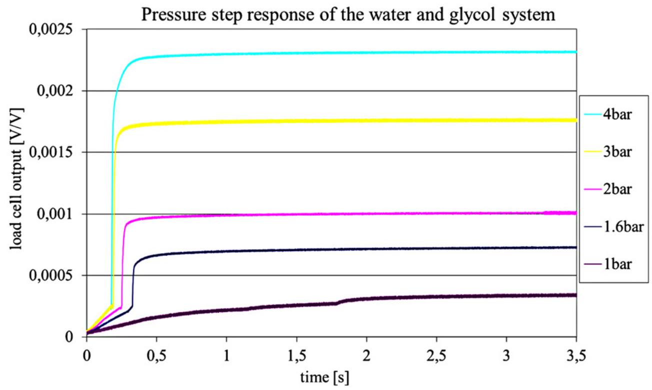

Fig. 10. Response at a pressure step of the compact system with water and glycol.

the latter to the fluid to be used. In particular, with reference to Figure 5, it can be noticed that the most compact configurations are preferable to those with longer tubes, if the same fluid is used (see curves "oil" and "oil (long pipes)").

Moreover, it is observed that the use of water and glycol is preferable with respect to the oil, since it produces a reduction of the RMS values at all the pressures; that means that the impact phenomenon is more effectively controlled.

Anyway, no very remarkable effect is acknowledged, with reference to the selection of fluid, being the length of pipes the most relevant parameter to be taken into account.

Further tests were carried out, to better understand the physical behavior of the pushing stage; a pressure step has been realized at the beginning of the connecting pipes and the time behavior of the pressure has been monitored along the connecting pipes, by means of a load cell. The pushing force between the knife and the anvil is the measured quantity. All these tests refer to static conditions (speeds of rotation of the knife equal to zero).

Figures 8–10 represent the main results describing the system response to a pressure step along the connecting pipes. In particular, Figures 8 and 9 show that the use of longer connecting pipes, with the same fluid under pressure (oil), involve higher response times. Figures 9 and 10 show that the system with water and glycol, as compared to the hydraulic one, presents a more regular behavior.

If these results are examined, remarkable differences among the systems can be detected in term of response speed and smoothness of the pressure rise with the time. If the "long tubes" and the compact one configurations are compared, the reduced efficiency of the former configuration is due to the increase of the response time of the system, which, consequently, is unable to promptly intervene to counteract the "rebound" of the cutting edges.

By comparing all these results, it can be pointed out that a relevant effect of pipe geometry, in particular a reduction of length, allowed us to significantly reduce the amplitude of vibrations by quickly and regularly transmitting the pressure fluctuations along the connecting pipes. The effect of fluid is less important. Furthermore, force transmission data confirm the right exercise pressure range.

Finally, simple data processing techniques demonstrate to be reliable, accurate and selective for possible on line implementation.

4 Conclusions

In this paper vibration measurements have been used to monitor the coupling conditions of knife and anvil cylinders in a cutting stage of a converting machinery for diapers production, in order to realize the best configuration to realize the coupling force. Many aspects have been considered for the design of this device: size of the system, length of pipes, liquid to be used in the hydraulic elements, pressure of exercise.

RMS of time acceleration diagrams and FFT spectra of envelope of vibration have been used for the data analysis in order to detect the most able technique for design and monitoring purposes.

The reduced uncertainty of the RMS method allows to better discriminate between trends corresponding to different configurations; therefore, it has been chosen to analyze measurement data in this paper, demonstrating to be reliable, accurate and selective.

It can be pointed out the effect of pipe geometry, in particular a reduction of length, allowed us to significantly reduce the amplitude of vibrations; a synergic effect, even though limited, of the type of fluid (water/glycol versus oil) has also been noticed. Force measurements in static conditions confirmed both these effects, suggesting some solutions to reduce system vibrations and to make more reliable the cutting operations, by quickly and regularly transmitting the pressure fluctuations along the connecting pipes.

Based on these results a comprehensive test program has been scheduled, in order to get experimental information useful for modeling of the cutting stage on the whole, looking at interaction between variables, including their effect on the cutting quality.

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