Merging complex information in high speed broaching operations in order to obtain a robust machining process

A del Olmo¹,³*, G Martínez de Pissón¹,³*, L Sastoque³, A Fernández³, A Calleja² and L N López de Lacalle¹,³

¹ University of the Basque Country (UPV/EHU), Dpt. of Mechanical Engineering. Plaza Torres Quevedo s/n, 48013, Bilbao
² University of the Basque Country (UPV/EHU), Dpt. of Mechanical Engineering. Calle Nieves Cano 12, 01006, Vitoria-Gasteiz
³ Aeronautics Advanced Manufacturing Centre (CFAA), University of the Basque Country (UPV/EHU), Parque Tecnológico de Bizkaia-Ed. 202, 480170, Zamudio, Spain

*Corresponding author: ander.delolmo@ehu.eus

Abstract: Current machine-tool users require more unattended machine centres due to the high competition in the global market of manufacturing. As a result, the control and monitoring systems became of utmost importance to detect the different events that could happen during the machining process. For example, broaching process is critical for firtree machining in turbine and automotive components. Tight tolerances and high productivity are the two main requirements for this kind of operation; therefore, it is essential to capture any anomaly during the process, that could damage the piece. This work proposes an alternative way of monitoring broaching process, based on machine internal signals, instead of the use of expensive force sensors for cutting force measurement. This paper presents an indirect monitoring procedure and its application in AISI 1045 high-speed broaching. The results showed the correlation between cutting force and servomotor power consumption, as a good parameter in the monitoring process of vertical high-speed broaching forces, capable of capture even changes in the cutting forces range of 500N.

Keywords: Machine data, Broaching, Indirect monitoring, Smart machine centres.

1. Introduction

New technological enhancements in automation show how the industry will evolve in the coming years to attain the highest productivity and the maximum reduction in production costs of the manufacturing process. Nowadays demand smart machines capable of working almost entirely unsupervised and even able to correct themselves in case of detecting any irregularity, to ensure that the workpiece will be between tolerances.

In different sectors, such as aircraft and automotive industries, one of the most important objectives is the full automation of the manufacturing process to increase productivity. Nevertheless, this must always come with the proper control of the machines to grant the optimal flow of the production. The unattended machining process requires smart techniques for the real-time detection of disturbances during the machining process. The principal strategies to obtain the information to enable this level of intelligence can be classified into two different categories: sensorization and sensorless methods.
Sensorization methods are based on the application of high and low-level sensors to collect a variety of heterogeneous machining magnitudes: forces (Kistler dynamometer), accelerations (accelerometers), sound pressure (acoustic sensors), spindle speed (tachometer), displacements (gauges), temperatures (thermocouple), etc. However, these devices are neither economically nor easy to adapt to all machines. Besides, some of them need extra equipment to work properly, such as a signal amplifier.

On the other hand, indirect monitoring methods are based on acquiring machine internal signals like power consumption or spindle current as process performance indicators. These indicators are numerical values with a direct link to relevant machining process magnitudes or tool wear conditions, giving real information about how the machining process is developing. For instance, Rivero [1] studies that internal signals related to the spindle and z-axis intensity consumption can be used for the monitoring of the tool wear in dry high-speed milling. Peña [2] analyses the signals of spindle torque to detect the apparition of burr in drilling operations of Al 7075-T6 aeronautical aluminium, while Li [3] evaluates the relationship of tool wear with spindle motor current and feed motor current. The use of consumption signals from the machine control shows significant advantages: no additional devices are needed; it is a less invasive method, which does not damage the workpiece; and the implementation in the machine control is much easier.

In the work presented here, the electromechanical broaching machine's data is used to estimate the cutting forces of the broaching process. Firstly, the broaching fundamentals and characteristics are explained providing a small sum up of the relevant work developed around this manufacturing technology. Secondly, the experimental procedure is described in detail in three main parts. The first one explains the data acquisition system and the step follow its implementation, while the next one explains the influence of the cutting process on the machine signals. The last section presents a real case, where the designed process monitoring system is applied. Finally, the conclusion obtained from this work is numbered.

2. Broaching fundamentals

The broaching process is commonly used since the 19th century to generate complex and accurate surfaces in a very short time. Originally, it was used for the production of pulley grooves and gears. Currently, it is widely used in many sectors, but mostly in the aircraft manufacturing and automotive components as well as in some turbine parts of the energy sector, because of the tight tolerances, they must fulfill to certify the right performance of whole packages.

Broaching is a particular material removal process where a tool called broach is used to cut the metal generally with a linear movement to obtain a cavity with a certain form such as fir tree. The broach cut in only one direction of the linear motion and how this movement is created divided different broaching machines in the hydraulic and mechanical or electromechanical broaching centre.

The shape of the groove like the surface finish [4] depends almost entirely on the tool geometry unlike other cutting processes such as end milling where the cutting parameter and tool orientation plays an important role to achieve a good surface. The main advantages of broaching process from other machining operations are the high feed and the amount of material that can remove just in one movement, obtaining huge productivity. The secret behind these competencies is the multiple teeth arranged strategically on the shaft or handle. The dimensions of the teeth increase along with the length of the tool, this escalation is called the "Rise Per Tooth" (RPT) parameter, the most important specification of the broach, and together with other machining conditions determinate the chip thickness as well as cutting forces [5]. In the figure 1 broaching main geometrical parameters are exposed.

Force modelling in a broaching operation is a challenging task due to complexity of the tool geometry. In broaching macroscopic force is the sum of force contribution of several teeth in contact with a workpiece. To simplify the problem, most models developed to date are based on the assumption that a broaching operation can be divided into a sum of multiple orthogonal cutting operations. Hosseini [6] probes that the orthogonal cutting approach does obtain a reasonable approximation of forces in broaching, especially in roughing operation.
Even though broaching is most commonly an internal process, where the tool passes through a hole and machines the desired form, can also be an external process. In this case, the operation resembles a full slot operation applied to a turbine disk. In this work, external face broaching tests are carried out in an electromechanical broaching centre with FAGOR® (CNC) software.

### Nomenclature and tool specification for a broaching operation.

| Parameter          | Symbol | Description            |
|--------------------|--------|------------------------|
| Relief angle       | α      |                        |
| Gullet space radius| r₁     |                        |
| Gullet space radius| r₂     |                        |
| Rake angle         | γ      |                        |
| Rise per tooth     | h      |                        |
| Tooth height       | H      |                        |
| Pitch              | P      |                        |
| Cutting edge radius| r      |                        |
| Land               | L      |                        |
| Skew angle         | λₛ    |                        |
| Tooth angle        | αₑ    |                        |
| Depth of cut       | αₚ    |                        |

**Figure 1.** Nomenclature and tool specification for a broaching operation.

The performed experiments were aimed at finding a relation between broaching machine's internal signals and the cutting forces of the machining process. They were carried out on a high-speed vertical electromechanical broaching centre developed by EKIN. It is a two-axis CNC machine with C and Z-axis. The rotary plate spins thanks to Fagor® FKM42 servomotor while vertical movement is produced by a gantry system where two Fagor® FKM85 servomotors generate linear movement using

**Figure 2.** Sensorless monitoring system diagram.

### 3. Experimental procedure

#### 3.1. Experimental set-up

The performed experiments were aimed at finding a relation between broaching machine's internal signals and the cutting forces of the machining process. They were carried out on a high-speed vertical electromechanical broaching centre developed by EKIN. It is a two-axis CNC machine with C and Z-axis. The rotary plate spins thanks to Fagor® FKM42 servomotor while vertical movement is produced by a gantry system where two Fagor® FKM85 servomotors generate linear movement using
a rack and pinion mechanism. Its specifications are 2000-rpm nominal speed at which nominal power is 15.5 kW and nominal torque is 46 Nm. These two motors were the source of machine internal data to analyze the broaching operation performance. This data acquisition is made using a Fagor® software program called Datalogger that allows obtaining the CNC variables, as well as in situ real data from the motor drivers, such as power and torque consumption each 4 ms. The machine tool and sensorless monitoring system are presented in figure 2.

As mentioned, this work aims to study the characterization of broaching process without any external device, only using machine data. The experimental procedure is divided into two different parts: an experimental part where several tests are realized to examine some critical machine signals and a validation part where obtained results are applied to a real broaching process.

3.2. Effect of cutting forces in machine internal signals
In order to obtain a relation between the internal signals and the cutting forces of the broaching operation, a batch of broaching cycles was executed for different cutting speeds. For this work, the servomotor’s power consumption data was chosen to be evaluated and related to cutting forces. The way to determinate was based on the next power balance equation (1) supposing that the cutting force developed during broaching operation can be approached to an orthogonal cutting.

\[ P = P_C + P_l \]  

where \( P \) is the sum of servomotors power consumption, \( P_C \) is the power use for cutting process and \( P_l \) is the power loss or power not use for metal cutting.

Consequently, as the cutting force and feed rate, which in broaching is equal to cutting speed, are applied in the same direction, enabling to calculate the work developed by the cutting force equation (2). In other words, the power need to cut the material with a determinate speed can be obtained as the product of the cutting force and feed rate, that enable to modelling the cutting force using the motor power consumption as it is shown in equation (3).

\[ P_C = \vec{F}_c \cdot \vec{v}_c = F_c \cdot v_c \]  
\[ P_C = \frac{P - P_l}{v_c} \]  

However, during the broaching process, not all the power is derived to cutting process itself due to there are other requirements in the machine. As a result, it is necessary to understand how the power supplied by servomotor’s is distributed during the operation. For that reason, instead of cutting material and produce unknown cutting forces, different weight loads were placed on the working platform to produce a known force in this batch of experiment.

![Figure 3. (a) The sum of both servomotors power consumption for different weight load at 15 m/min cutting speed (b) Mean values of the total power consumption at 15m/min.](image-url)
Through these tests is possible to measure how sensible is power consumption to the increment of effort that happens during a real broaching operation, here artificially produce by the increase of the weight placed in the working platform as shown in the figure 3. Besides, since it is known how much energy it is necessary to move these loads to a certain speed because the mass of its load is familiar, it is possible to quantify the amount of energy not use for metal cutting in the broaching process.

This process is repeated for different cutting conditions until figure 4(a) is obtained. It is generally observed that the power consumption follows a linear performance for different cutting forces. As the cutting speed rises, the slope of the function of power consumption also increases. On the other hand, the power loss during the process is calculated since the mass of each weight is acquainted. As it is shown in figure 4(b), the power losses remain almost steady for low cutting speed and it varies a bit at higher speeds.

![Figure 4](image)

**Figure 4.** The effect of cutting forces on motors power consumption and power loss at different cutting forces.

For modelling, the cutting forces during broaching operation using the information about the power consumed by the servomotors, it is more interesting to plot the power losses that occur during the cycle as a function of the cutting conditions. As shows in figure 5 the power losses have a clear quadratic relation with cutting forces, where the variation of values is completely represented by the function since $R^2 = 1$.

![Figure 5](image)

**Figure 5.** Power loss average as function of cutting speed.

Once it is known how the power loss happen during the broaching cycle it is possible to apply these signals to monitor the cutting forces of broaching operation.
3.3. Indirect monitoring method apply in a real broaching process

The chosen material to apply the indirect monitoring method was alloy AISI 1045, due to is a very common alloy used in many sectors such as automotive and energy. The chemical information is given in Table 1. The material was supplied in the form of a disk of external diameter 500 mm and internal diameter 320 mm, besides the thickness of the disk was about 37 mm.

Table 1. Average time analysis of different slot machining strategies.

|                  | C  | Mn | Si | P  | S  | Fe  | Others |
|------------------|----|----|----|----|----|-----|--------|
| Hardness         | 0.45 | 0.65 | 0.30 | 0.035 | 0.035 | 97.83 | -0.7   |
| Young’s Modulus  |    |    |    |    |    |     |        |
| Tensile Strength |    |    |    |    |    |     |        |
| Density          |    |    |    |    |    |     |        |
| Specific Heat    |    |    |    |    |    |     |        |
| Melting Temperature |    |    |    |    |    |     |        |
| Thermal Conductivity |    |    |    |    |    |     |        |

The tool selected for this batch of experiment is a AISI 02 High Speed Steel (HSS) broach for roughing operation, which was already used to avoid the initial worn out of the cutting edges, which often leads to a sharp increase of the cutting forces before they stabilise (Figure 6).

Some broaching cycle were carried out with different cutting conditions, recording the power consumption of both motors during the operations for after work with them and obtain the process cutting forces. The result is shown in Figure 7.

![Figure 6. AISI 02 broaching tool for roughing.](image)

![Figure 7. (a) The total power supply by both servomotors, (b) Total force supply by both servomotors.](image)

Finally, it is necessary to remove the force used to raise the working platform and the workpiece during the process in order to obtain the force used exclusively for the metal cutting process. As shown
in the figure 8, the variation of the cutting speed does not greatly affect the cutting force developed in broaching [7].

![Figure 8. Broaching Z cutting force.](image)

4. Conclusions
This work presents an indirect way of checking the performance of the broaching technique. High-speed broaching is a critical manufacturing operation in turbine and automotive components. For that reason, these kinds of processes are highly sensorized to control each aspect of the metal cutting. Nevertheless, this work studies a different way of controlling the broaching technique using only machine internal information to oversee the procedure. The main conclusions derived from this work are cited hereafter:

- Some machine internal data do not provide enough information about the machining process; however, this work shows that the servomotor power consumption signal is a good parameter to monitor the cutting forces and it is sensitive enough to record even the lower cutting forces around 500N.
- Observing the power consumption of both servomotors during the first batch of the experiment, was detected that in the electromechanical broaching process, the main power loss of the process is almost only dependent on cutting speed and the losses can be estimated using an empiric quadratic formula.
- Using only a power consumption signal of the servomotors is possible to monitor the cutting forces quite precise during external broaching, since the energy need to cut the metal can be related to the work developed by the machine due to the main cutting force is applied in the same direction of the cutting speed.

As a result of the results obtained, different research lines are opened in which it will be necessary to carry out more research that can support in a more precisely way the work carried out in this project through obtaining a greater amount of data.

- Firstly, it would be interesting to implement an external device to measure the cutting forces in broaching of AISI 02 and then compare them with the data obtain using an indirect method in order to establish the accuracy of the developed method.
- In line with the global tendency of the 4.0 Industry and the use of artificial intelligence in manufacturing, consisting on developing neural networks and algorithms for the enhancement of the product, manufacturing sectors, It is easy to implement machine data to this kind of software than the signals captured by external equipment such as piezoelectric devices, since this kind of data do not need any data preparation.
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