# Embedded smart bearing for condition monitoring of rolling mill for Industry 4.0

# Embedded smart bearing for condition monitoring of rolling mill for Industry 4.0

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**Abstract**
The implementation of smart manufacturing in steelmaking includes a continuous monitoring of cluster cold rolling mill to perform an effective activity of prognosis, diagnosis and maintenance. Some back bearings are applied to the outer crown of backup rolls within the mill cage to play the role of physical node, for a cloud-based interconnected monitored system. The concept of smart bearing, equipped with sensors, is here revised and fitted to purpose. Since main goals of monitoring are detecting any abnormal operation of mill and identifying any damage within the bearing, some key measurements to be performed and a trade-off of sensors technologies are proposed, through the Model Based Systems Engineering approach, according to the Industry 4.0.

Structural mechatronics, Systems engineering, smart manufacturing, smart bearing, fibre optics sensors

## 1. Introduction

Enabling the smartness of manufacturing systems is a main goal of strategy known as "Industry 4.0" [1]. It implies a wide digitalization of the product lifecycle development and full traceability [2]. Systems connectivity for monitoring, diagnosis and prognosis is a challenging issue and involves network services, supported by the Internet (IoT). A physical node is crucial to connect sensors measuring the performance of working system to the network, and to transfer numerical data. A mechanical bearing equipped with sensors can play this role, as a smart device. It is an innovative solution, when applied to huge industrial equipment and harsh environment, like in steelmaking plants [3]. The wide literature about smart manufacturing do not suggest a systematic approach to design an interconnected industrial system. Selecting the main functions of nodes, identifying relevant parameters to be measured, and data to be transferred, performing the trade–off among available technologies need to be suitably driven. This is done by the Model Based Systems Engineering [2]. The most promising configuration for a smart bearing to monitor a cluster rolling mill can be found and its concept design defined.

## 2. Smart bearing concept

The 'smart bearing' is a mechanical bearing equipped with sensors, to be used to detect any abnormal operation of rolling mill (out-monitoring), and to warn the user remotely about any damage occurring inside the bearing itself (in-monitoring). Sensing technology is an issue of design, and has to be compatible with mill cage layout. Power feeding is even important. Autonomous service is a matter of investigation. It uncouples system and power line, by resorting to some energy harvesting [4]. System duty cycle and service have both to be precisely determined. Design criteria for the trade-off of technologies are system complexity, reliability, availability, maintenance, safety and cost. The smart bearing has to be embedded into a larger system, like a cluster cold rolling mill. It includes several rolls in contact, namely from work to backup, together with a set of back bearings, whose inner ring is fitted upon some fixed pins and outer one rotates (Fig.1).

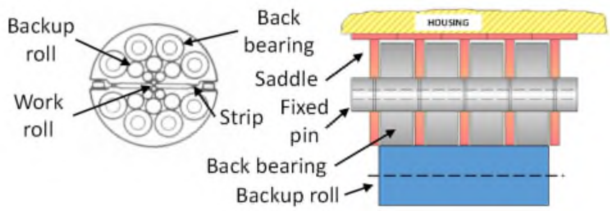



**Figure 1.** Sketch of a cluster mill for cold rolling.

Cold rolling of metallic strip is performed through several passes in sequence, each one at faster speed, as strip thickness decreases [4]. Rolling action is huge, up to 5 MN, for a steel strip thick 0.5 through 3 mm. Frequency bandwidth of dynamic phenomena is large, considering rotation of rolls and vibration of mill cage, undergoing chatter at some kHz. As Fig.1 shows, any sensor applied to back bearing needs to be embedded in the mill cage, between saddles, which allow positioning the pin to assure a uniform contact with rolls.

## 3. System development

A preliminary design is performed through a Model Based Systems Engineering (MBSE) approach [2]. Main features are summarized in Fig.2. Customer needs are identified and transformed into technical requirements, considering different use cases. Requirements are allocated to functions, being identified by a functional (nominal behaviour) and a dysfunctional (behaviour with failures) analysis, respectively, and an architecture is proposed as a Functional Breakdown Structure (FBS). Similarly, functions are allocated to logical blocks. They describe components to perform activities, but they are not yet associated to commercial products. A logical layout follows (LBS). Logical components are then substituted by commercial devices, and physical layout (PBS) describes the integration of components and subsystems. Those three analyses allow some activities, as the trade-off of technical solutions and the system verification (requirements fulfilment) and validation (customer satisfaction).

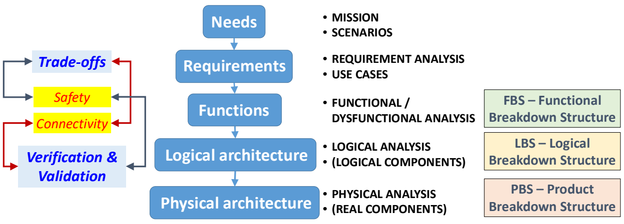



**Figure 2.** Design actions and products according to the MBSE.

### *3.1. Needs, requirements, functions*

The smart bearing satisfies two kinds of needs, being related to its nature of mechanical support, and to its role of physical node of an interconnected system. Needs motivate requirements and allocated functions. As a mechanical support, bearing the load applied by backup rolls, in all passes, at every strip speed, is a main function. Lubrication shall be compatible with operational temperature, to be lower than 70°C, preferably no higher than 40–50°C. Surface of outer ring shall be regular and without defects, as life shall be guaranteed, for given number of hours, without material rupture nor failure. Configuration shall be compatible with harsh environment and layout of mill cage. Use of special bearing for cluster mill is mandatory. Safety, quality and cost complete this screening.

As a physical node, a continuous in and out monitoring, with some capabilities of prognostics and alarming, is a customer need. It requires selecting measures to be performed in operation, and consequently sensors to be applied, their power feeding, and communication system and performance.

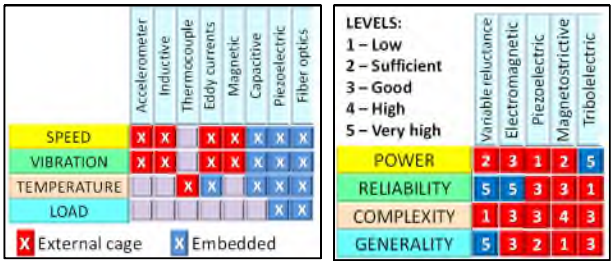
### *3.2. Analysis*

Roll vibration and slip are detected by a difference in spin speed of bearings fitted on each pin. Therefore, measuring of spin speed of outer rings in each pin is required. To prevent problems related to high temperature and load in rolls, both will be monitored. The mill cage remains closed in operation, to prevent any accidental access of operators or dispersion of lubricant, against the risk of fire. This requires that either cage or smart bearing is equipped with sensors, power supply, local memory, and telemetry system. Since mill and bearing vibration amplitude and frequency reveal damage of raceways and rollers, they will be measured. Saddles impose severe limitations to bearing access and affect the selection of sensors. The inner ring is quite thin, therefore embedding sensors in this layout looks questionable. By converse, fixed pins are massive and can be exploited to deliver lubricants, but even to support other services, like allowing wire connections.

### *3.3. Technological trade-off*

Provided that mechanical layout of bearings is defined by special products applied to cluster mill, by requirement, design focuses on the monitoring system based on sensors. In the literature many solutions are proposed for similar applications. They can be compared as in Fig.3(a). Principles of measurement are compared by considering whether an external cage or an internal arrangement is required. Some commercial solutions of smart bearing include some sensors applied to housing or directly embedded inside the bearing, within rings or linked to inner cage. The need for an autonomous power generation is an issue for sensor selection. Particularly, it is associated to a suitable energy conversion, as in Fig.3(b).

Basically, two solutions appear as the most promising for this application. One embeds transducers within the material of inner ring, being fixed. It includes a piezoelectric MEMS package, a vibration energy harvester, a telemetry unit and a wireless connection [6]. A second one is based on the fiber optics [7]. It provides a multiple measurement per each fiber, can be operated at high temperature, is less sensitive to noise, but is connected and powered by an electronic unit.




(a) (b)

**Figure 3.** Screening of sensors technologies for inner and outer use (a) and energy harvesting systems (b).

Limitations in inner ring thickness, of room between rings and saddles, of number of wireless sensors (six per pin, up to 48) and several interferences make weak the selection of embedded piezostacks. By converse, a sensor based on fiber optics can be embedded into the thin inner ring and can exploit the pin as a gate to the light source, coupler and decoupler units, to be located near the cage, and connected via wireless to cloud. Moreover, this solution looks intrinsically safe against the risk of fire and explosion (ATEX Standards), and is compatible with high humidity, lubricant and temperature.

### *3.4. Design synthesis*

Functional analysis defined benefits and drawbacks of proposed solutions, but prediction of sensor duty cycle can be performed quantitatively only by investigating the dynamic behaviour of mill cage, through a physical model, as in a multibody dynamic simulator. Bandwidth to be monitored is up to 5 kHz, for a strip speed of 500 mpm and spin speed of back bearing of 600 through 900 rpm. Therefore, sensor duty cycle should be done in 1 ms, for sampling and processing, 1 ms for receiving and transmit, with 98 ms of stand-by, and power consumption of some mW. Data elaboration requires a processor operating at 1 GHz, with a RAM of 4 GB. Encryption of data is required to protect the system and use the cloud.

## 4. Conclusion

Despite the current wide application of wireless MEMS sensors the MBSE revealed that fiber optics better fit requirements of the cluster mill. Among typical enabling technologies of "Industry 4.0" [1] big data analysis, cyber security, cloud, industrial internet, advance manufacturing technology and simulation are all involved. More than single sensor units, a modular monitoring package per each cage shall engineered. This study provides a PBS for the development of a test rig, for an experimental validation of the proposed solution.

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