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A COMBINED VIBRATION-BASED CONDITION MONITORING AND FINITE ELEMENT ANALYSIS APPROACH FOR FAILURE ASSESMENT OF ANNULAR GAS SCRUBBING SYSTEMS

Nicolás Alderete and Federico Larco

Noietec S.A., Buenos Aires, Argentina
email: nicolas.aalderete@gmail.com

Gonzalo Echaniz

Ternium Siderar, Technological Services, San Nicolás, Buenos Aires, Argentina

Gas cleaning systems play a fundamental role in blast furnace operations having the two-fold responsibility of efficiently cleaning furnace gas and controlling the top pressure of the blast furnace. As a result, stable furnace operations as well as economic iron ore production, coupled with ever increasing productivity rates require fully integrated, adaptable and trouble-free gas scrubbing systems. Particularly, annular or ring slit (RS) gas scrubbers are amongst the most widely used and proven technologies in the steel making industry. Despite their relevance, scarce references relating these systems to vibration issues can be found in the literature. Since May 2015, a series of abnormal events have been registered in the gas scrubbing system of the blast furnace of Ternium Siderar mill Gral. Savio, the only flat steel products manufacturer in Argentina. The events had started out as unusual displacements and clashes in one of the 3-Cone arrangement and led to failure events which compromised the normal operation of the facility. In order to determine the causes of the aforementioned problematic, a series of studies have been conducted comprising both computational and on-the-field vibration monitoring techniques. Multichannel acceleration measurements allowed for the identification of frequency ranges in different operational conditions ranging from normal to pre-failure scenarios. In parallel, a finite element model of the gas scrubbing assembly was developed to characterize the modal behaviour of the system and its components and to evaluate the impact of different faulty scenarios. The comparison between measurements and simulated results presented very good accord which allowed for the identification of critical zones and the establishment of a model on which to evaluate future design or maintenance improvements. This paper presents the results of the implemented approaches and discusses the basis for future work on the subject.

Keywords: Scrubber, condition monitoring, vibrations, FEM

1. Introduction

Blast furnace gas coming out from the top of the iron furnace carries small particles of coke, iron ore and fluxes. These elements have to be removed before the gas could be considered for secondary use in other facilities. In addition to the removal of the particulate content within the gas, both gas temperature and pressure must be adjusted to the particular requirements of the subsequent facilities.

The aforementioned gas transformation takes place along the Blast Furnace Gas Line, depicted in Fig. 1 [1].

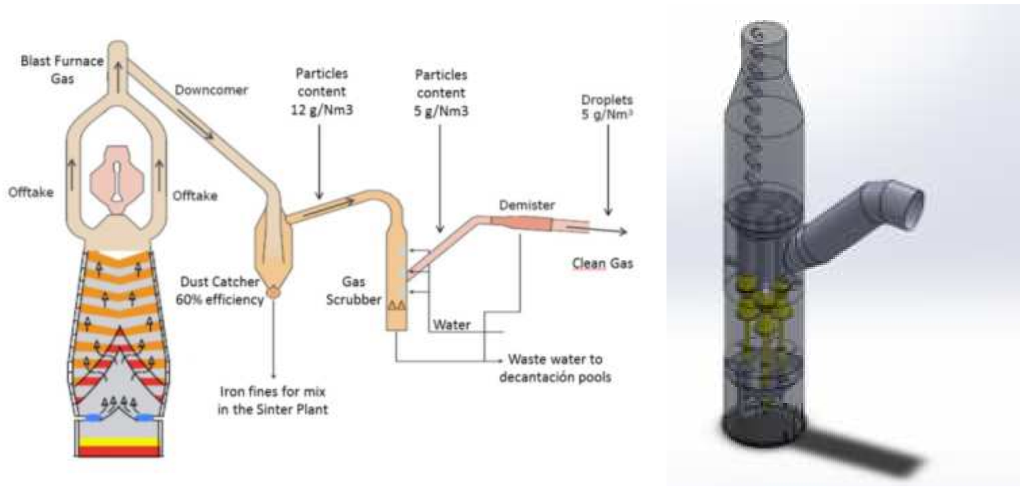

Figure 1: Blast furnace gas line and gas scrubber

Amongst all the components shown in Fig. 1 the Gas Scrubber is where the chilling of the gas and final cleaning occurs. This happens due to the formation of interfaces between the highly turbulent flow of furnace gas (with its stream of particles) and the water supplied by sprinklers. The numerous interactions between these elements create an intense mixing which promotes the transferring of gas particles to the water through complex mechanisms such as: inertial interception, turbulent diffusion and flow line interception.

Particularly, the scrubber under study has three Annular Gap Elements (AGE) which regulate the top pressure of the blast furnace. This is achieved by changing the annular gap size by means of an enforced axial displacement of the cones and through the adiabatic expansion which follows the exit of the gas and ultimately contributes to its chilling. In order to achieve the maximum cleaning efficiency, the flow distribution through the annular gap must be symmetrical. To such end, the alignment between the cone and the Venturi must be precisely correct.

The annular gap elements usually follow a parallel arrangement inside the gas scrubber as shown in Fig. 1. Each annular gap element presents a simple configuration in which there are two auxiliary components, namely bushings, which ensure the proper alignment of the cone and Venturi. A hydraulic cylinder at the base is responsible for the axial movement needed for pressure regulation and at the top a central sprinkler contributes to the gas cleaning as described above. Figure 2 shows the main components of an annular gap element.

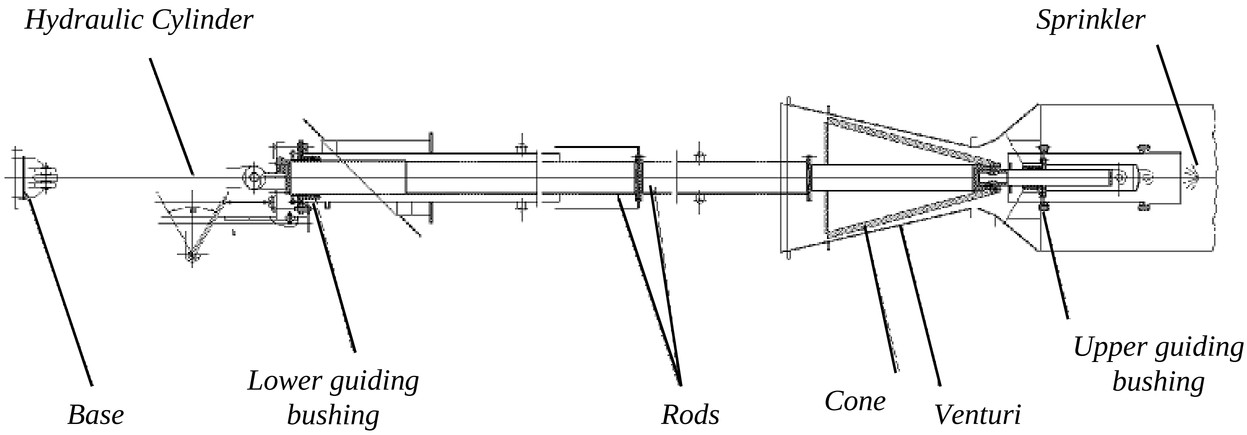

Figure 2: Annular gap scrubber main parts

2. Description and chronology of events

Starting around April 2015 (9 years after the AGE's installation) displacements of considerable magnitude were detected by the equipment inspector at the junction of the lowest rod and the hydraulic cylinder of AGE Number 2. Consequently, in May 2015 a first approach of condition base monitoring (CBM) was implemented to allow for the control of the situation by means of changes in operational parameters of the AGE until equipment intervention were possible. During the period between May-December 2015 AGE 2 worked at a fixed point of an 8% opening to control the overall vibration value while AGEs 1 and 3 operated with automatic regulation. At the July 2015 Blast Furnace Shut Down (BFSD) a visual inspection could be made identifying the breakdown of the upper shaft of the cone. The characteristics of the equipment coupled with the type of failure drawn suspicions to problems within the guiding system of the AGEs.

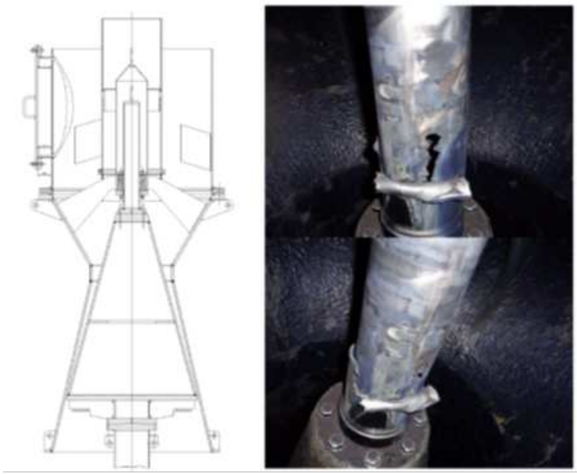

Figure 3: Broken upper shaft

In December 2015, major reparations were undertaken in which the Cone, Cone Upper Shaft, Venturi and Upper Bushing were changed. However, just a few weeks after the reparation tasks abnormal movements started again (along with a rise of the overall vibration values). Following inspection at the February 2016 BFSD it was found that 8 out 12 bolts at the rod joints were broken. Failure analysis of the joint pointed to fatigue as the main cause of failure. This was a result of excessive rod movements which resulted from joint looseness.

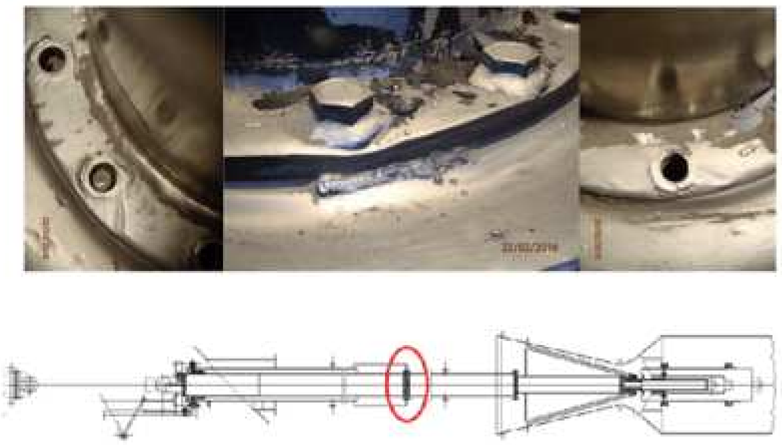

Figure 4: Broken bolts at rod junction

In March 2016 the compromised joints were repaired but soon after the overall vibration values of AGE Number 3 began to rise, reaching in a short period of time the values first detected in AGE Number 2. Again, a similar procedure based on the tuning of operational parameters of the cones was implemented until inspection and reparation was possible at the BFSD in September 2016. Once again, the failure cause was the breakdown of the upper axis of the cone of AGE Number 3.

3. Vibration-based condition monitoring

3.1 First approach to condition monitoring

At May 2015 a first attempt of a Condition Based Monitoring System was formulated. As the problems detected were related to oscillating repetitive movements the monitoring variables of choice were vibrations. At first, only waveform and overall vibration values were considered but after further analysis full spectrum was included. Given that during operation of the blast furnace most of the gas scrubber components are inaccessible, measurements points were selected at the end of the lower rod inside the hydraulic cylinder room. Because of the annular gap elements' configuration it was natural to assume that the vibrations at these points would be related to the ones at the cones. Hence, recollection of information in the three axes shown in Fig. 5 was undertaken:

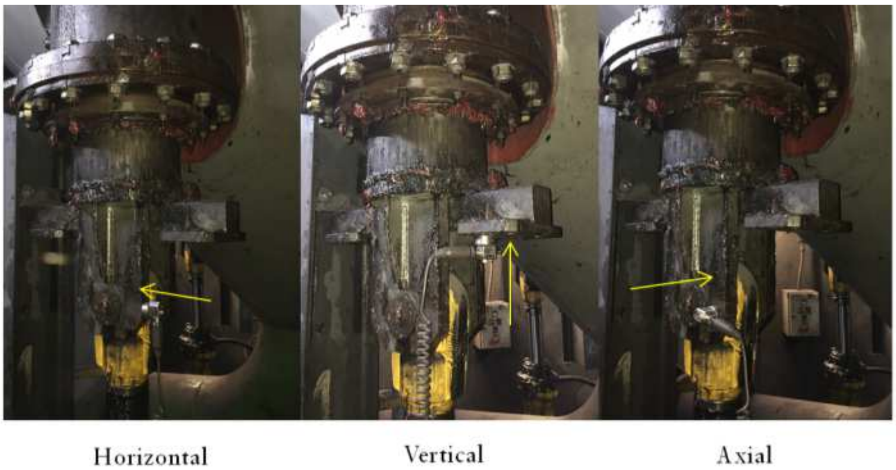

Figure 5: Measurement device location and directions of interest

Given that most of the wave energy was located in the low frequency region, velocity was chosen as the sole monitoring variable. A one week period between measurements was chosen.

Alarm limits were defined by the condition monitoring technician at two levels: 4 mm/s. for alarm and 7 mm/s. for danger.

3.2 Improvement of the condition monitoring formulation

After a period of successful implementation of the condition-based monitoring, an integral re-evaluation of the system, the gathered data and further investigation of the faulty modes allowed for the improvement of the condition-based monitoring formulation. This improvement was based on two new analyses which were undertaken to attain a deeper understanding of the vibration spectrum and overall behaviour of the equipment. The two mentioned approaches were: continuous multivariable measurements and finite element modal study of the annular gap elements.

Continuous multivariable data gathering began in April 2016. It was implemented in all three annular gap elements which allowed for a complete representation of the behaviour of the AGEs under the different conditions of gas flow and top pressure present in the blast furnace ranging from start-up to regime-like operational conditions. The recollected variables being now vertical, axial and horizontal velocities and accelerations represented an enhancement of the previous monitoring stage. Review of the newly obtained full spectrums made it possible to identify and define two distinct frequency bands or ranges as shown in Table. 1 and depicted in Fig. 6 below:

Table 1: Frequency bands after full multivariable spectrum analysis

	Frequency Band 1 Related to normal operational conditions [cpm] (Hz)		Frequency Band 2 Related to faulty operational conditions [cpm] (Hz)	
Variable	Min.	Max.	Min.	Max.
Horizontal	485 (8.03)	655 (10.92)	705 (11.75)	955 (15.92)
Axial	510 (8.50)	750 (12.50)	1020 (17.00)	1380 (23.00)
Vertical	595 (9.92)	805 (13.42)	723 (12.05)	980 (16.33)

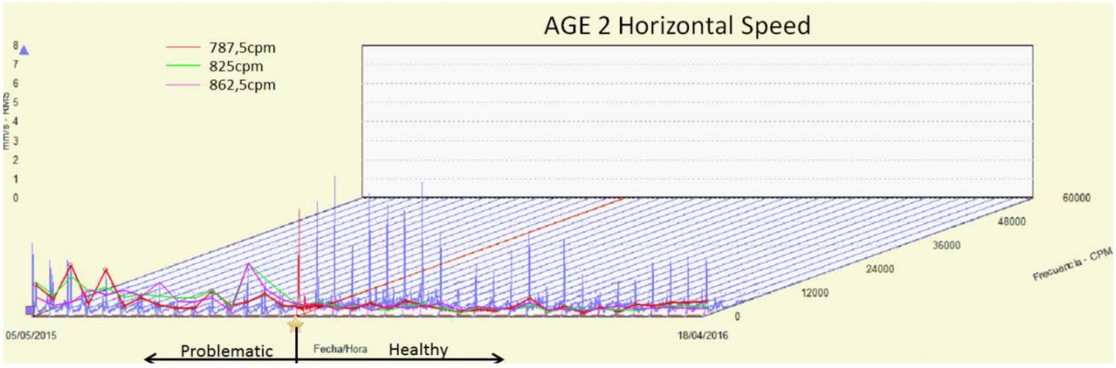

Figure 6: Sample FFT measurements and frequency bands for AGE Number 2 Horizontal Speed

Low frequency bands were also identified for horizontal and axial displacements in the frequency band 2. These frequencies were centred in 120cpm (2Hz) with a 5% scatter.

4. Finite Element Model

A finite element model of the gas scrubber depicted in Fig. 2 was built on Altair Hypermesh® to perform modal analysis and obtain the system's natural frequencies under different boundary conditions.

4.1 Characteristics

The main components, which include the Cone, Venturi, pipes and flanges, were meshed using 2D quadrilateral and triangular first order shell elements. For all shell meshes, control of shell offset was implemented for accurate representation. An average element size for shells of 10mm, resulting in a mesh density of 148733 elements, was used to ensure proper convergence and accuracy. Additionally, 1D beam elements were used for the representation of flange bolts, hydraulic cylinder rods and sprinkler pipes. In order to account for the mass of the shower heads, non-structural masses were incorporated to the model. Consistent mass matrices were employed in all models.

The presence of hydraulic fluid grants the positioning system a higher compliance than those of the hydraulic cylinder components alone. To account for such characteristic 1D spring elements carrying stiffness solely in the vertical direction were employed. The stiffness of the spring was calculated by considering an effective stiffness which adds the contributions of both the hydraulic fluid and the hydraulic cylinder. The hydraulic fluid stiffness is given by its bulk modulus which depends on composition, temperature and pressure; whereas the cylinder stiffness depends on material stiffness (E), Poisson ratio (ν), cylinder thickness (t) and diameter (d). The aforementioned can be written as [2]:

$$\frac{1}{k_{eff}} = \frac{1}{k_{cyl}} + \frac{1}{\dfrac{Et}{2d\left[1+2(1+\nu)\dfrac{t}{d}\right]}} \quad . \tag{1}$$

On a first approach, a model of a single cone assembly was evaluated with the objective of gaining quick insight on the phenomenon and later comparing it to the actual 3-Cone system. If the results of the single cone and 3-cone arrangement presented good accord, then a simpler model could be used for preliminary studies concerning configuration changes and potential maintenance improvements.

4.2 Boundary conditions

Given that the abnormal displacements and clashes suggested problems arising from faulty guiding systems, special focus was set on the boundary conditions of the system. These include the following: upper and lower guiding systems (Bushings), hydraulic cylinder clevis and anti-twist system, connections between the cones and the main structure and connections between the three cones

As mentioned above, the critical boundary conditions were the ones representing the upper and lower guiding systems. As mentioned in Section. 1, guiding is achieved by means of bushings. Given the impossibility of incorporating contact features in modal analysis, these were incorporated by means of multipoint constraints connecting the involved nodes according to the operation condition under study (Open or Closed Cone). Figure 7 depicts the connections established between the inner and outer pipes which stand for the upper guiding system.

For the single cone model, a symmetry condition was imposed on the nodes where pipes which connect the three cones arrive. Subsequently, for the complete model, these constraints were replaced by beam elements connected to the shell elements by means of interpolation elements, namely RBE3.

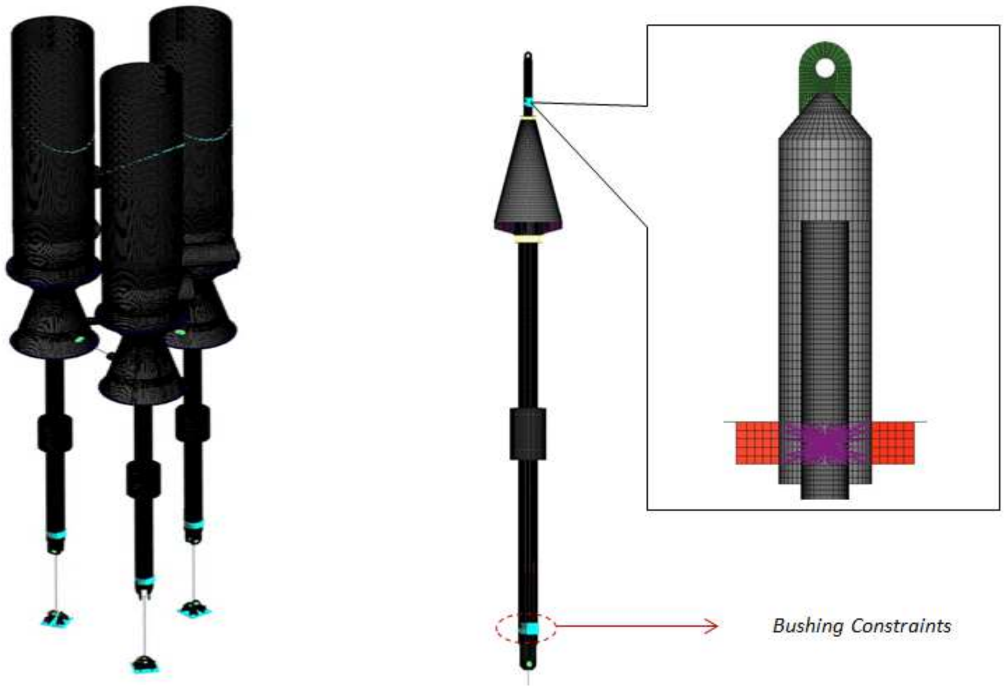

Figure 7: Finite element model of the gas scrubber and bushing constraints model

4.3 Results

Results from modal analysis for the single cone system are presented in Table. 2 and Table. 3 for the different operation conditions (open or closed cone) and for the particular scenarios of normal and faulty upper or lower guiding systems. In the following, *A.B.* stands for Axial Bending, *H.B.* for Horizontal Bending, *V.* for Vertical and *T.* for Torsional mode. The highlighted frequency values and mode shapes are the ones relatable to the frequency bands identified after continuous multivariable vibration monitoring shown in Table. 1.

Table 2: Modal analysis results, Operational Condition 1: Closed AGE

Finite Element Modal Analysis Results Operational Condition 1: Closed Annular Gap Element						
	Scenario 1 Guiding System Normal		Scenario 2 Lower Guiding Faulty		Scenario 3 Upper Guiding Faulty	
Mode	Frequency [cpm] (Hz)	Mode Shape	Frequency [cpm] (Hz)	Mode Shape	Frequency [cpm] (Hz)	Mode Shape
1	691.0 (11.5)	*A.B - Cone*	521.9 (8.7)	*H.B. – Cone*	109.2 (1.8)	*A.B. - Cone*
2	700.4 (11.7)	*H.B. - Cone*	640.1 (10.7)	*A.B. – Cone*	110.4 (1.8)	*H.B. - Cone*
3	713.2 (11.9)	*V. - Cone*	713.1 (11.9)	*V. – Cone*	712.8 (11.9)	*V. - Cone*
4	740.2 (12.3)	*Other*	740.2 (12.3)	*Other*	739.8 (12.3)	*Other*
5	750.0 (12.5)	*Other*	749.9 (12.5)	*Other*	749.4 (12.5)	*Other*
6	1095.0 (18.3)	*T. - Cone*	1093.6 (18.2)	*T. - Cone*	861.6 (14.4)	*T. - Cone*
7	1940.9 (32.3)	*Other*	1709.8 (28.5)	*H.B. - Cone*	1149.0 (19.2)	*A.B. - Cone*
8	2136.5 (35.6)	*Other*	1856.0 (30.9)	*Other*	1159.8 (19.3)	*H.B. - Cone*

Table 3: Modal analysis results, Operational Condition 2: Open AGE

Finite Element Modal Analysis Results Operational Condition 2: Open Annular Gap Element						
	Scenario 1 Guiding System Normal		Scenario 2 Lower Guiding Faulty		Scenario 3 Upper Guiding Faulty	
Mode	Frequency [cpm] (Hz)	Mode Shape	Frequency [cpm] (Hz)	Mode Shape	Frequency [cpm] (Hz)	Mode Shape
1	608.6 (10.1)	*A.B - Cone*	446.6 (7.4)	*H.B. – Cone*	120.0 (2.0)	*A.B. - Cone*
2	621.1 (10.4)	*H.B. - Cone*	531.4 (8.9)	*A.B. – Cone*	120.0 (2.0)	*H.B. - Cone*
3	713.4 (11.9)	*V. - Cone*	713.9 (11.9)	*V. – Cone*	714.0 (11.9)	*V. - Cone*
4	740.2 (12.3)	*Other*	740.2 (12.3)	*Other*	739.8 (12.3)	*Other*
5	749.9 (12.5)	*Other*	749.9 (12.5)	*Other*	749.4 (12.5)	*Other*
6	1025.6 (17.1)	*T. - Cone*	1025.3 (17.1)	*T. - Cone*	858.0 (14.3)	*T. - Cone*
7	1923.7 (32.1)	*Other*	1529.6 (25.5)	*H.B. - Cone*	1272.0 (21.2)	*A.B. - Cone*
8	2109.7 (35.2)	*A.B. - Cone*	1674.0 (27.9)	*A.B. - Cone*	1278.0 (21.3)	*H.B. - Cone*

Good accord can be seen between the numeric results and the frequency bands from Table. 1. This is particularly so for the open cone condition. The agreement allowed drawing two main conclusions. Firstly, that the structure was effectively being excited in frequencies close to the system's natural frequencies. Secondly, and, most importantly, that the generic faulty condition band in Table. 1, once suspected to be related to faulty guidance, was effectively related to ill-functioning of the upper guidance system. This not only allowed to conduct repairment tasks aimed at the upper guidance system but also confirmed the finite element model as a valuable tool for diagnostics.

5. Summary and conclusions

A combined condition based monitoring and numeric analysis approach was implemented for the understanding and resolution of vibration related problems in blast furnace gas scrubbers. Despite the criticality of the component in the iron making process scarce references of similar issues can be found in the literature. The applicability of a continuous condition-based monitoring together with a finite element analysis of the equipment under different working scenarios allowed for the identification of frequency bands which could be successfully related to malfunctions in critical components of the equipment. As a result insight on the failure modes was gained and a model was established to serve as diagnostic tool for problems analysis and as a basis on which to evaluate future design and/or maintenance improvements.

The results of the presented approach have enabled both the use of the equipment without any unscheduled blast furnace interruptions and the anticipation to major breakdowns. In addition, a new decision making routine, was established on which to evaluate and solve problems. The new routine, depicted in Fig. 8, has allowed a considerable saving of resources for inspection of the equipment given the tasks needed to access the annular gap elements (scaffolding, man-holes opening, etc.).

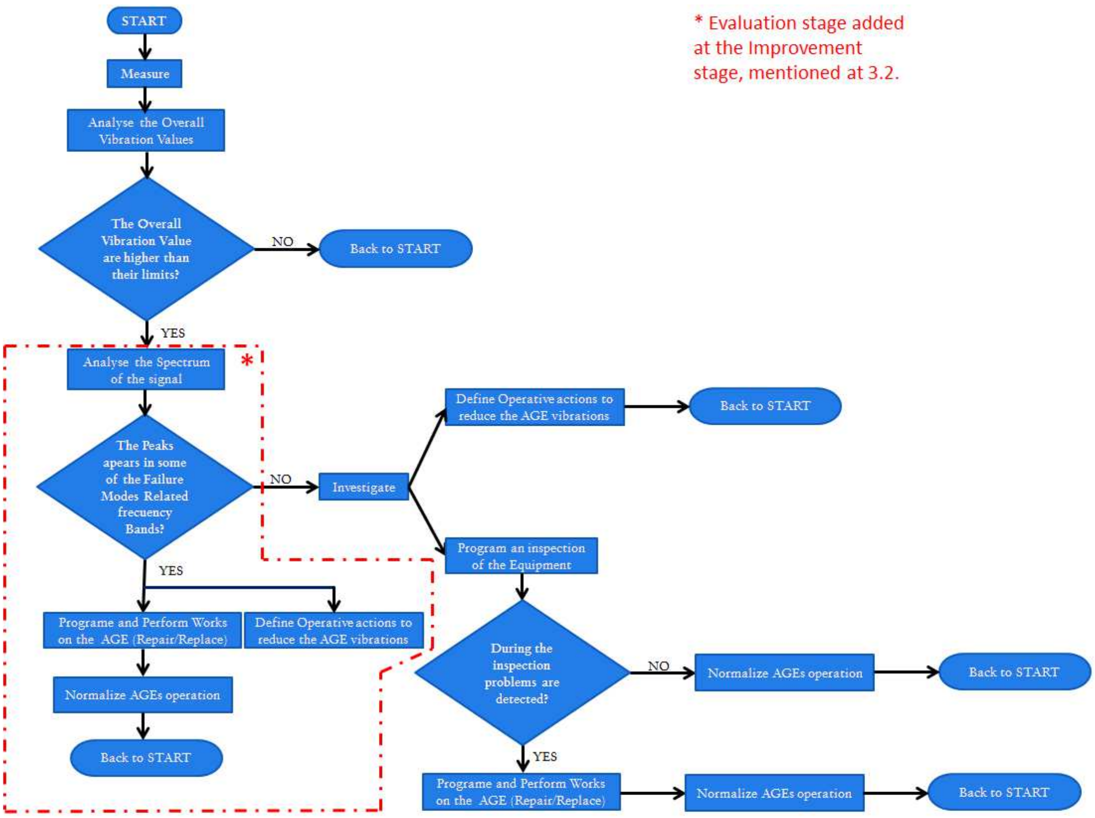

Figure 8: Decision making routine for AGE assessment

The nature of the vibrations induced in the structure is one of the main topics for future study. In this line, Computational Fluid Dynamics studies pose the most viable method to assess whether the problem might be related to vortex induced vibrations.

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