Vibration-Based Monitoring of Gas-Stirring Intensity in Vacuum Tank Degassing

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Liquid steel is typically stirred in a vacuum tank using argon gas injection to achieve a homogeneous composition and high-purity steel. The aim of this work is to study the effect of vessel vibration on the operational state monitoring of the gas stirring in a vacuum tank degasser. Following an extensive analysis of vibration features, the root mean square (RMS) of vertical velocity is found to be the best feature for the measurement of the stirring intensity caused by the volumetric gas injection rate into the ladle. Smoothing is conducted using a centered median filter with a window length of 21 s. In this work, the operational state monitoring of gas stirring is described using a ladle responsiveness value (LRV). This describes the ability of a ladle to generate the maximum amount of vibration with the minimum amount of argon gas. The LRV summarized for each ladle reveals significant differences between them. Correspondingly, a rolling ladle responsiveness value (rLRV) is used for online monitoring of possible gas leakages. The rLRV can also be used for the online monitoring of the stirring efficiency and as its comparison with the overall efficiency of a specific ladle or all ladles.

1. Introduction

The main tasks of ladle treatments in steelmaking meltshop are alloying, deoxidation, degassing, and heating of steel. As steelmakers strive to reduce variance in composition and temperature as well as improve energy use and yields, various methods, including vibration[1–14] optical,[15,16] and acoustic measurements[17,18] have been proposed for indirect measurements. In ladle treatments, gas stirring serves to promote the homogenization of the steel bath and intensification of chemical reactions. However, the malfunctioning of the gas injection from the bottom of the ladle is a common problem. The efficiency of gas stirring is of great importance for steel grades that require high inclusion purity.

Several approaches have been envisaged for measuring the efficiency of bottom-blowing in plant use. Table 1 shows a summary of studies on the application of vibration measurements for meltshop processes. The vibration monitoring approach is based on the vibrations associated with gas injection. The ladle vibration spreads from the metal bath onward to the surrounding mechanical structure, from which the vibration can be measured without disturbing the process. The vibration intensity can be used, e.g., for monitoring scrap melting,[7] vessel oscillation,[2–4] slopping,[3] and rate of gas stirring.[6–14]

Controlling the intensity and duration of gas stirring is important for ensuring a high degree of productivity and quality control. This is not an easy task, however, as the process involves high temperatures and turbulent molten steel. In the case of vacuum tank degassing, a further hindrance is the poor reachability. To achieve more accurate control, a clear insight into the gas-stirring performance should be obtained. Yenus et al.[10] studied the monitoring of gas stirring in steelmaking ladles using a physical model. Based on principal component analysis (PCA), they established that the contribution of the vibration amplitude in the x, y, and z direction to the first principal component and hence to the mixing was almost equal. In a later study, Yenus et al.[13] compared different accelerometer locations and found that the frequency content of the vibration data was almost the same regardless of the measurement location. The possibilities for using vibration-based measurements extend beyond maintenance-related aspects. For example, Hwang et al.[14] used a vibration-based system not only for monitoring gas leakages but also for predicting desulfurization kinetics in a ladle. The inputs of their model were the bottom plug status and calibrated vibration signal. A fairly good agreement with experimental data was obtained regardless of the bottom plug status. The relationship between the gas flow rate and the vessel vibration has also been studied with a water model.

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Table 1. Studies on the application of vibration measurements for meltshop processes.

| Process                        | Application                     | Reference  | Year |
|-------------------------------|---------------------------------|------------|------|
| Electric arc furnace          | Estimation of molten state control | Schmidt et al.[11] | 2015 |
| Argon–oxygen decarburization  | Monitoring of vessel oscillation| Fabritius et al.[9] | 2005 |
|                               |                                 | Odenthal et al.[9] | 2010 |
|                               |                                 | Wuppermann et al.[9] | 2013 |
| Basic oxygen furnace          | Monitoring of foam level and slopping control | Brämming et al.[9] | 2011 |
| Ladle treatments              | Monitoring of gas-stirring intensity in ladle treatments | Burty et al.[9] | 2006 |
|                               |                                 | Kostetsky et al.[7] | 2007 |
|                               |                                 | Min et al.[9] | 2013 |
|                               |                                 | Behera et al.[9] | 2014 |
|                               |                                 | Yenus et al.[9] | 2016 |
|                               |                                 | Alia et al.[11] | 2019 |
|                               | Monitoring of gas-stirring intensity in vacuum tank degassing | Pylvänäinen et al.[12] | 2016 |
|                               |                                 | Yenus et al.[13] | 2018 |
|                               | Monitoring of gas-stirring intensity and prediction of desulfurization kinetics | Hwang et al.[14] | 2014 |

by Alia et al.[11]. Their results show that the positioning of the accelerometers has a significant effect on the relation between the gas flow rate and measured vibration.

In earlier work,[12] a vibration-based stirring intensity monitoring system was implemented at SSAB Europe, Raah, Finland. The aim of the current work was to use this measurement setup to find a variable that relates the vessel vibration to the gas flow rate and to study the use of vessel vibration for the operational state monitoring of gas stirring.

2. Experimental Section

In this work, the experimental data was measured from a vacuum tank degasser in the secondary metallurgy area at SSAB Europe, Raah, Steel Works. The stirring was conducted using argon gas. Argon was injected through two porous plugs at the bottom of the ladle. The typical duration of a single vacuum treatment was approximately 27 min. Typically, the ladle was partially relined after 80 tappings, after which it was used for another 80 tappings before a full relining.

The vibration intensity depends on the location of sensors at the vacuum tank degasser and the measurement direction. In this examination, the measurement points were selected based on earlier experience and ease of sensor installation. The main target of the measurement was the ladle vibration. The aim was to provide a low-maintenance installation, which would allow for the changing of the ladle without additional disturbance to the operation. Consequently, accelerometers were placed on the support beam located outside the vacuum tank, as shown in Figure 1. Both the horizontal and vertical directions were measured. In addition to the ladle support beam vibration, also the vibration of two gas lines were measured in the vertical direction. The gas flow rate information was produced by gas flow controllers which can output the actual flow rate as a 4–20 mA current signal. These signals were electronically isolated, converted into a voltage, and connected to a data logger.

The measurement system was set up to log all the measurement channels continuously. The duration of the measurement campaign was about 5 weeks and data from 334 stirring events were logged.

2.1. Data Acquisition, Signal Processing, and Feature Extraction

Data logging was performed using hardware manufactured by National Instruments. The data logger was programmed using LabVIEW software. A schematic representation of the measurement system is shown in Figure 2. The system had four one-axial accelerometers connected to an NI9234 module; two channels of the NI9215 were used for gas flow measurements; in addition, the system included a CompactRIO data logger and an external USB storage. The chassis of the data logger had a built-in temperature sensor, the signal of which was also stored as auxiliary information. Attention was paid to record any possible phenomena at a fairly wide frequency band, and therefore the sampling frequency of 25.6 kHz was used for all the channels as a discrete option of the data logger. According to sampling theorem,[19] the sampling frequency of 25.6 kHz enabled visibility to frequencies up to 12.8 kHz. The data acquisition modules were equipped with built-in antialiasing filters.

The data processing was conducted in two stages. First, preprocessing was conducted to separate stirring events from the data. To separate the stirring events from the continuous data stream, the gas flow rate was used as trigger information. When the stirring was not active, the gas flow was obviously stopped. The stirring process included a continuous gas flow that typically lasted 27 min. Based on this information, the start of stirring was triggered once the gas flow rate was greater than 25 Nl min⁻¹ for at least 10 s. After experimentation, it was
concluded that the selected trigger condition performed well enough and more complex rules were not needed. The preprocessing consisted of the following steps: 1) separation of the stirring events from the (nominally) continuous data stream; 2) combining 1 min files into a single file representing one degassing treatment; and 3) removing all the degassing treatments which were known to be unsuccessful or otherwise corrupted. After preprocessing, 273 out of 334 logged stirring events were suitable for further analysis.

After this, the preprocessed data were analyzed by calculating features representing the intensity of the vibration and analyzing their relation to the gas flow. The features used in the vibration intensity evaluation were so-called weighted $l_p$ norms[^21] utilizing a generalization presented in ref. [21]. This norm is defined as follows

$$\|x^{(\alpha)}\|_p = \left( \frac{1}{N} \sum_{i=1}^{N} |x_i^{(\alpha)}|^p \right)^{\frac{1}{p}} = \left( \frac{1}{N} \right)^{\frac{1}{p}} \left| \sum_{i=1}^{N} x_i^{(\alpha)} \right|^p$$  

(1)

where the order $p$ of the norm is a real number, $N$ is the number of observations in the signal, $x$ stands for displacement, and $\alpha$ is the order of the derivative with respect to time. The use of a weighting factor $1/N$ is generally reasonable to make norms calculated for signals of different lengths comparable with each other. The orders of norm in this study included the values $0.5 \leq p \leq 2.0$, with a step of 0.5 and the norms were calculated for the displacement, velocity, and acceleration signals. The primary processing was implemented in the MATLAB and R software packages using library and custom-made functions, and consisted of the following steps done for the data in each stirring event:

**Step 1:** Windowing using Tukey (i.e., tapered cosine) window function with a 0.025 times the acceleration signal length long tapering part at both ends, zero padding the signal length to the next power of two, calculating the discrete Fourier transforms (DFT) using the fast Fourier transform (FFT) algorithm, bandpass filtering the DFT to 1–2000 Hz and integrating the acceleration signal to the velocity and displacement signals.

**Step 2:** By using Equation (1), calculating values of the generalized norms of orders 0.5, 1.0, 1.5, and 2.0 for the horizontal and vertical vibration displacement, velocity, and acceleration using one second window length.

**Step 3:** Summing the gas flow rates of both gas lines and calculating a running average for the summed gas flow rate using one second window length ($\approx 25,600$ observations).

**Step 4:** Partitioning of the stirring event into three stages (initial stage, vacuum stage, and last stage) based on the vacuum tank pressure. The vacuum stage is active when absolute pressure of the vacuum tank is less than or equal to 0.2 kPa.

**Step 5:** Collecting the gas flow rate and generalized norms (calculated in steps 2 and 3) from the vacuum stage for further processing described in the next steps.

**Step 6:** Calculating smoothed generalized norms using centered median filtering with a window length of 21 s.

**Step 7:** For the correlation analysis to come in step 9, some variation in the gas flow rate was desired. For this reason, stepwise changes in the gas flow rate (hereafter referred to as changepoints) were detected using the following detection rule: range of the gas flow rate within a time window of 5 s is equal or greater than 36 Nl min$^{-1}$ (i.e., 0.6 Nl s$^{-1}$). Detected changepoint is acceptable if: no start of the vacuum stage nor other changepoint(s) are identified within 40 s before the changepoint candidate, and no end of the vacuum stage nor other changepoint(s) are identified within 80 s after the changepoint candidate.

**Step 8:** If two or more acceptable changepoints are detected, samples of the gas flow rate and unsmoothed and smoothed generalized norms are collected from the time periods of 40–10 s before and 50–80 s after each changepoint. Otherwise return to step 1 for processing the next stirring event. Here, we have excluded the transient time period 0–40 s after the changepoint and also 10 s before and after this transient time because at those time instants the median filtered norm values are affected by the transient period.
Step 9: Calculating a Pearson’s correlation coefficient values: between the gas flow rate and unsmoothed generalized norms, and between the gas flow rate and smoothed generalized norms using the values collected from the time periods mentioned in step 8.

Step 10: Saving the values of the correlation coefficient and return to step 1 for processing the next stirring event.

Step 11: For each smoothed and unsmoothed generalized norm, calculating the median and interquartile range (IQR) of the correlation coefficients compiled from 115 stirrings.

As the outcome of steps 1–11, the root mean square (RMS) of vertical velocity was found to be the best feature for the measurement of the stirring intensity. That feature was used for the further data analysis described in the following steps:

Step 12: Defining a general responsiveness value for the ladle for each stirring event by calculating the ratio of the cumulative sums of the gas flow rate and the selected vibration feature.

Step 13: Defining an online monitoring value for the ladle responsiveness. The value is used during the stirring to measure the ratio between the vibration rate and the gas flow rate. The aim of the value is to reveal when there is an insufficient gas flow to a ladle that can be a sign of a leakage in the argon gas lines.

3. Results and Discussion

3.1. The Vessel Vibration during Stirring

The behavior of the gas flow rate and the vacuum tank pressure varies depending on the phase of the gas-stirring process. Therefore, the stirring process was divided into three stages based on the vacuum tank pressure, as shown in Figure 3.

In the initial stage, argon gas valves are opened and the gas flow rate increases. The argon gas flows through its channels into the steel bath. Once the gas flow has reached the steel bath, the vibration intensity of the ladle increases, and the gas flow rate falls. This is seen as a typical up-and-down peak in the gas flow rate and the vibration intensity at the beginning of the initial stage. Then the gas flow rate increases stepwise until an adequate vibration intensity, i.e., the gas-stirring intensity, has been reached. The vacuum tank pressure is equivalent to an atmospheric pressure. At the end of the initial stage, the absolute pressure of the vacuum tank starts to decrease toward the required level, which is below 0.3 kPa.

In the vacuum stage, the gas flow rate has reached an adequate level to generate a desirable stirring intensity. In case of leakage or blockage in the argon gas lines, the gas flow rate can be adjusted to maintain the gas-stirring intensity at the desirable level. The absolute pressure of the vacuum tank reaches a desirable level below 0.3 kPa. During the vacuum stage the vacuum tank pressure curve has minor peaks (see Figure 3), which appear when alloying additives are added to the steel bath. In the last stage, the gas flow rate is reduced, and the vacuum tank pressure rises back to the atmospheric level. Thereafter, the gas flow channels are closed, and the stirring is complete.

The preliminary data exploration revealed that most of the analyses in this work should be conducted to the vacuum stage (see Figure 3) to mitigate the effect of disturbing factors related to the start and end of the stirring process. Even then, the data of separated stirring events display a great deal of diversity between stirrings. Candidate vibration features included displacement, velocity, and acceleration with the orders 0.5, 1.0, 1.5, and 2.0 of the generalized norm in vertical and horizontal directions.

3.2. Evaluation of Vessel Vibration Intensity

The stirring power can be expressed as a function of gas flow rate as follows[12]:

\[
\dot{\varepsilon} = \frac{\dot{V}_G}{M} \left[ RT \ln \left( \frac{p_{in}}{p_{out}} \right) + R(T - T_m) \right]
\]  

(2)

where \( \dot{\varepsilon} \) is the stirring power [W kg\(^{-1}\)], \( \dot{V}_G \) is the volumetric gas flow rate [Nm\(^{-3}\)min\(^{-1}\)], \( M \) is the mass of the melt [kg], \( R \) is the universal gas constant [J mol\(^{-1}\)K\(^{-1}\)], \( T \) is the melt temperature [K], \( T_m \) is the inlet temperature [K], \( p_{in} \) is the inlet pressure [Pa], and \( p_{out} \) is the outlet pressure [Pa]. Equation (2) suggests

![Figure 3. Division of the gas-stirring process into three stages. a) The vibration intensity, b) gas flow rate, and c) absolute pressure of the vacuum tank are shown on the same time scale. Vibration intensity is depicted by using the RMS of the vertical velocity.](image-url)
that the stirring power and the volumetric gas flow rate have a linear relationship. Yenus et al.\textsuperscript{[10]} concluded that stirring power and bath circulation speed had a strong linear relationship with vibration. In view of these considerations, the dependency of vessel vibration and argon gas flow rate was assumed to be linear, and therefore in this work, the goodness of vibration feature is measured by the Pearson’s correlation coefficient between the feature candidate and the argon gas flow rate.

The gas-stirring treatments were categorized into three types: A) short dehydrogenization and denitriﬁcation treatment, B) decarburization treatment, and C) long dehydrogenization and denitriﬁcation treatment. Correlation analysis was initially conducted for type A and type C treatments by handling them as one group, whereas type B treatments were analyzed as an own group. However, analysis results demonstrated no difference in correlation between treatments groups, and consequently they were handled as one group in the subsequent analysis.

The initial stage of the gas-stirring process shown in Figure 3 indicates a time lag between the gas flow rate and the vibration intensity, i.e., when the gas flow strongly increases in a stepwise manner, the vibration intensity follows after a lag period. In the vacuum stage, where the vibration feature search was conducted, the lag phenomenon is challenging to visually detect because the gas flow rate is relatively stable. However, more detailed analysis conducted for the vacuum stage data revealed that after a stepwise change in the gas flow rate, vibration intensity settles to the new level approximately within 40 s. In this work, this 40 s transient time is not included in the sample selection of the correlation analysis.

Figure 4 shows the search results for the Pearson’s correlation coefficient between the gas flow rate and vibration features. Smoothing using the centered running median with a 21 s long window was conducted for the vibration features to increase the correlation with the gas flow rate. The smoothing effect can clearly be seen in Figure 4 where the probability density functions related to smoothed vibration features are obviously more concentrated on the right, i.e., they have higher correlation values compared with density functions related to unsmoothed vibration features. The same effect is demonstrated also by higher median values of the correlation coefﬁcients calculated for the smoothed vibration features. This phenomenon is obvious especially in the vertical displacement and velocity.

Probability density functions related to both smoothed and unsmoothed vibration features display negative correlation coefﬁcients in few stirring events, especially in acceleration. This is typically caused by outliers included in the samples of the smoothed and unsmoothed vibration features collected for the correlation coefﬁcient calculation. Density functions were calculated using a Gaussian kernel function with 0.05 bandwidth.

Figure 4 shows that all generalized norm orders of the vertical velocity have the strongest unimodal concentration close to the correlation of 1.0. Hence, it can be concluded that under the conditions of this work, the vertical velocity with the centered median smoothing using window length of 21 s is the best vibration quantity for the gas-stirring intensity measurement.

Yenus et al.\textsuperscript{[13]} measured vibrations from a 160 t vacuum tank degasser and also found out that the linear relationship was different for each stirring, i.e., the constant and slope of the linear fits varied, even though the correlations were always signiﬁcant during a single stirring. Thus, if the data from all the stirrings were combined, the correlation disappeared. The same observation was found to hold also for the measurements of this work and that is the reason why the correlation coefﬁcients, which form the distributions of Figure 4, were calculated separately for each stirring.

The signal processing used by Yenus et al.\textsuperscript{[10,13]} differs from the approach used in this work and consequently a direct comparison of the studies is not permissible. First, the vibration features that were tested by Yenus et al.\textsuperscript{[10,13]} were the sums of the amplitudes of the frequency components in 10 Hz intervals from all three directions, which were then transformed using PCA. Then they decided that the most informative frequency intervals are such, where the ﬁrst principal component dominates the most.

In this study, the vertical and horizontal vibrations were studied separately. From Figure 4 it can be concluded that a single axis vibration sensor is sufﬁcient for stirring intensity monitoring. The vibration features used are time domain norms of acceleration, velocity, and displacement ﬁltered to the range 1–2000 Hz. As vertical velocity and displacement had the best correlations in this study, and as integration ampliﬁes the low-frequency content of a signal, we can say that it is the lower end of the range 1–2000 Hz that has the best correlation with the gas flow rate.

The observations of the studies of Yenus et al.\textsuperscript{[10,13]} agree well with the ﬁndings of this work. As for a 160 t vacuum tank degasser, Yenus et al.\textsuperscript{[13]} reported that the vibration feature from the range 60–70 Hz had a strong linear correlation with the gas ﬂow rate. In their physical modeling study, Yenus et al.\textsuperscript{[10]} found that all the vibration features that correlated well with bath recirculation speed and stirring energy were found from 10 Hz wide frequency ranges which did not exceed 330 Hz.

The median and IQR values of the correlation coefﬁcients shown in Figure 4 are presented in Table 2. These statistics are typically used to measure the magnitude and dispersion of the data when the distribution is strongly skewed, as in this case. In Table 2, IQR is a measure of dispersion of the correlation coefﬁcients and represents the difference of 75th percentile, known as Q3 and 25th percentile, known as Q1. Thus, the IQR = Q3 − Q1.

When comparing the displacement and velocity in the horizontal measurement direction in Table 2, difference within their median and IQR values is negligible for both smoothed and unsmoothed vibration features. This is also demonstrated in Figure 4 by the nearly identical shape of the distribution curves of the horizontal displacement and velocity.

Comparison of median values within each vibration feature reveals that the median value of the smoothed vibration feature is systematically greater than the median value of the unsmoothed vibration feature. The same comparison conducted for IQR within each vibration feature shows that the IQR values are constantly smaller in the smoothed vibration feature except in the case of the horizontal acceleration when the opposite is true. The smoothed vertical velocity exhibited the largest median values along with lowest IQR values.

When the median and IQR of the Pearson’s correlation coefﬁcient for the smoothed vertical velocity are examined across the generalized norms of orders 0.5, 1.0, 1.5, and 2.0, it becomes
evident that the variation of median values in the range of 0.90–0.92 is negligible compared with the constant IQR value of 0.17. As the effect of order of the generalized norm to the median of the correlation coefficient is very small, all the studied norm orders for the smoothed vertical velocity can be considered suitable.

Based on the aforementioned considerations, in the subsequent analysis of this work we choose to use the smoothed RMS of the vertical velocity. The RMS corresponds with the order 2.0 of the generalized norm. The RMS was chosen because it is widely used in many applications.

3.3. Indicators for Ladle Condition Monitoring

Sealing the argon gas lines from the gas valve to the steel bath is essential for efficient gas stirring. Therefore, in this research, the

![Figure 4. Probability density functions for the Pearson’s correlation coefficients between the gas flow rate and the vibration features. Each section represents the distribution of correlation coefficients and their median values calculated from 115 stirrings for the smoothed and unsmoothed vibration feature.](image-url)
approach to the operational state monitoring of gas stirring is based on the idea of generating the maximum amount of vibration with the minimum amount of argon gas. This attribute can be quantified using a ladle responsiveness value (LRV) that is defined by the ratio of the cumulated vibration and the cumulated argon gas during a stirring. To mitigate the effect of disturbing factors caused by high variability in the gas flow rate (see Figure 3), the LRV is calculated based on the data of the vacuum stage.

**Figure 5** shows the principle of LRV for the ratio of areas under the vibration feature curve and the gas flow rate curve. When comparing the low, medium, and high LRV columns, areas under the vibration feature curve are reasonably same. When comparing areas under the gas flow rate curve, they decrease strongly from left to right, which, and due to being denominator of the ratio, strongly increases the LRV. When comparing the cases in Figure 5, stirring with a high LRV is the most efficient because the cumulated vibration during the vacuum stage has been generated with the minimum amount of argon gas. Approximately the same amount of the cumulated vibration has been generated in the stirring with a low LRV, but the required amount of argon gas was many times greater. Therefore, the efficiency of a stirring event with a low LRV is poor. It should also be noted that, in addition to leakages in the argon gas lines, another potential reason for the poor LRV could be variation in the ladle alignment to its mechanical interface in the vacuum tank, which causes variation in the vibration transfer from a ladle to the ladle support beam where accelerometers were installed.

To develop a good overall understanding of the responsiveness of an individual ladle, LRVs from several stirrings per ladle should be collected. In this examination, ladles with data from a minimum of ten stirrings were chosen for the ladle responsiveness analysis.

The boxplot shown in **Figure 6** provides a summary of LRVs calculated for each ladle. The boxplot is often used to visually show the distribution of continuous numerical data and skewness of it. An actual “box” of the boxplot represents the IQR, and a line across the box represents the median. Outliers, i.e., an exceptionally high or low values (x) of the dataset, are defined according to the following rule: IF[x < Q1 − 1.5 IQR] OR (x > Q3 + 1.5 IQR] → Outlier. A lower whisker is drawn from the Q1 to the smallest value of the dataset, excluding outliers, and a higher whisker is drawn from the Q3 to the greatest value of the dataset, excluding outliers. Outliers are displayed by individual dots located outside of the whisker ends, and they are accompanied by ID number of stirrings.

**Figure 6** shows that certain LRV level may be exceptionally high, i.e., an outlier for one ladle, but the same LRV level is within the expected LRV range of another ladle. For example, when the stirring no. 103 (see Figure 6) has an exceptionally high LRV for ladle L8, the same LRV level is not exceptional for ladle L6 due to its different expected LRV range. A significant difference between the ladles can be visually identified by a fictional horizontal line crossing the boxes. If the line overlaps the boxes of compared ladles, they may be significantly different, but statistical test is needed to confirm it. If the line does not overlap the boxes, compared ladles are probably significantly different. For example, ladles L9 and L20 are significantly different as well as ladles L3 and L16. Ladles L3 and L4 can be overlapped by a horizontal line. They may be significantly different, but a statistical test is needed to confirm it. The boxes for ladles L6 and L17 are so well overlapping that even without a statistical test it can be concluded that they do not have significant difference.

Based on Figure 6, two distinct ladle groups can be identified using LRV = 56 as an approximate borderline. Ladles L3, L7, and

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**Table 2.** Median and IQR of the Pearson’s correlation coefficients between the gas flow rate and the smoothed and unsmoothed vibration feature.

| Measurement direction | Vibration quantity | 0.5               | 1.0               | 1.5               | 2.0               |
|-----------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|                       |                   | Median | IQR   | Median | IQR   | Median | IQR   | Median | IQR   |
| Vertical              | Acceleration      | 0.79 (0.50)   | 0.40 (0.46) | 0.79 (0.51)   | 0.39 (0.47) | 0.80 (0.52)   | 0.39 (0.47) | 0.81 (0.51)   | 0.41 (0.45) |
|                       | Velocity          | 0.92 (0.57)   | 0.17 (0.34) | 0.91 (0.56)   | 0.17 (0.33) | 0.91 (0.55)   | 0.17 (0.32) | 0.90 (0.53)   | 0.17 (0.32) |
|                       | Displacement      | 0.87 (0.50)   | 0.19 (0.25) | 0.87 (0.52)   | 0.19 (0.26) | 0.88 (0.52)   | 0.19 (0.28) | 0.88 (0.51)   | 0.18 (0.29) |
| Horizontal            | Acceleration      | 0.71 (0.50)   | 0.49 (0.41) | 0.71 (0.49)   | 0.50 (0.43) | 0.70 (0.50)   | 0.49 (0.44) | 0.70 (0.49)   | 0.49 (0.45) |
|                       | Velocity          | 0.75 (0.49)   | 0.26 (0.31) | 0.76 (0.51)   | 0.25 (0.31) | 0.77 (0.52)   | 0.24 (0.32) | 0.78 (0.53)   | 0.24 (0.32) |
|                       | Displacement      | 0.75 (0.49)   | 0.26 (0.30) | 0.76 (0.51)   | 0.25 (0.30) | 0.77 (0.52)   | 0.25 (0.30) | 0.78 (0.53)   | 0.24 (0.31) |

*Values without brackets represent statistics calculated for smoothed vibration features and values with brackets represent statistics calculated for unsmoothed vibration features.*
L9 belong to the “efficient” group because their boxes are above the borderline. The “inefficient” group consists of ladles L16 and L20 because their boxes are completely below the borderline. The rest of the ladles are challenging to classify because their boxes overlap each other and with the aforementioned groups.

In principle, the responsiveness properties, i.e., the LRV value within a ladle, may change over time due to continuous wear of the ladle lining. However, in the studied data the LRV value was found to have only a low correlation ($r = 0.42$) with the number of stirrings after partial or full relining of the ladle.

### 3.4. Detection of Gas Leaksages

To reliably control the tightness of the argon gas lines from a gas flow controller to a ladle, the process operator should have a real-time indicator to monitor. The indicator should react to a gas leakage as reliably as possible. In this research, an examination was conducted for an indicator that is based on the LRV.

Unlike the LRV, as an individual number per stirring, the gas leakage monitoring indicator is a time series that consists of ratios of vibration feature values and gas flow rate values. The indicator vector is called a rolling ladle responsiveness value (rLRV). Due to the high variability in the gas flow rate and the vibration intensity (see Figure 3) in the initial stage, the rLRV is calculated based on the data of the vacuum stage. As in the LRV analysis, ladles with data from a minimum of ten stirrings were chosen for the rLRV analysis.

**Figure 7** shows five cases of the rLRV vector and corresponding vibration intensity, as well as the gas flow rate vectors used for the rLRV calculation. Vectors in the vibration intensity column are plotted on the same scale, so are the vectors in the gas flow rate column. Adjacent rLRV vector plots on the same row are identical and all rLRV plots are on the same scale. Five cases, i.e., five rows, have been collected from five stirrings, with a different ladle ID each. They represent the behavioral diversity of the rLRV. A horizontal median line on the left rLRV column is calculated based on all the rLRV data of the ladle in that row, whereas the overall median line on the right rLRV column is determined based on the rLRV data of all ladles.

The lower control limit (LCL) is based on a 0.01 quantile and is defined from an empirical distribution of the rLRV data of either individual ladle (in the left rLRV column) or all ladles (in the right rLRV column). When the rLRV behavior does not change in comparison with the data used for the definition of the LCL, the likelihood that the rLRV values will fall below the LCL is 1%. This is considered a rare event and thus indicates a deterioration of the rLRV. In addition to the tightness monitoring of the gas lines, the rLRV can be used for real-time efficiency monitoring.

**Figure 7** shows how the general rLRV level of each stirring can be reviewed when the ratio of the vibration intensity and the gas flow rate levels is compared. The rLRV level difference between the stirrings can be clearly seen in the rLRV plots in the rightmost column when they are compared with the overall median of the rLRV. For example, stirrings no. 64 and 240 are opposite one another from the rLRV level point of view. Figure 6 shows that stirring no. 64 as an outlier of ladle L17 has an exceptional high LRV compared with the expected LRV range of that ladle. Stirring no. 240 is an outlier of ladle L9 and has an exceptionally low LRV for ladle L9. In the stirring no. 64, the vibration intensity level is high compared with the gas flow rate, as shown in Figure 7. Consequently, as depicted in the rightmost column, the level of their ratio, i.e. the rLRV level, is high compared with the overall median. In stirring no. 240, the vibration intensity level is low compared with the gas flow rate. Respectively, the rLRV level calculated based on them is low compared with the overall median. When the rLRV of the stirring no. 240 is monitored in comparison with the generic condition of the ladle, the ladle median and LCL are used. In case the rLRV monitoring is done in comparison with the overall condition of all ladles, the overall median and LCL are used.

The top row in Figure 7 shows stirring no. 171 done in ladle L3. According to Figure 6, the ladle L3 is classified as “efficient.”
The same phenomenon can be seen from the two adjacent rLRV plots of the stirring no. 171 where the ladle median is greater than the overall median. The rLRV of the stirring no. 171 is normal for the ladle L3 because the rLRV fluctuates around the ladle median. The rLRV of the stirring no. 171 is slightly better than normal when all ladles are considered because the rLRV curve locates mainly above the overall median.

The second row in Figure 7 shows the stirring no. 200 in ladle L20. Ladle L20 is classified as “inefficient,” which can also be seen from the rLRV curves where the ladle median is less than the overall median. The rLRV is reasonably normal for ladle L20, whereas it is worse than normal when all the ladles are considered.

The bottom row in Figure 7 shows how the lag between the gas flow rate and the vibration intensity affects the rLRV curve in stirring no. 209. At the beginning of the vacuum stage, i.e., before time of 200 s, the gas flow rate rapidly increases and reaches its maximum at the first gridline. Due to the lag, the vibration intensity only starts to increase at the time of 200 s. During the lag period, the rLRV drops dramatically because the gas flow rate, i.e., the denominator of the ratio defining the rLRV, increases whereas the vibration intensity, i.e., the numerator of the ratio, remains stable. When the vibration intensity reacts to the change of the gas flow rate and starts to increase, the rLRV increases and remains stable on the lower level. This demonstrates that a sudden drop in the rLRV curve does not necessarily mean a gas leakage. In case the rLRV curve remains below the LCL and does not increase after the lag period, this most probably indicates a gas leakage.

A topic for future work would be to study the frequency spectrum content of the ladle vibration in more detail to identify the frequency bandwidth that has a better correlation with the gas flow rate, and consequently with the gas-stirring intensity. In addition, possible nonlinear relationships between the gas flow rate and vibration intensity could be investigated. Finally, a closer look would also be taken at the possible relationship between the LRV and the number of stirrings after the ladle relining, and to improve the coefficient of determination by modifying the LRV and including more explanatory variables in the model. A potential advantage of the vibration-based monitoring system is that the information on the availability of the gas injection can also be used to support calculations for the efficiency of the treatment itself.

4. Conclusions

Controlling the intensity and duration of gas stirring is important for ensuring a high degree of productivity and quality control. Gas leakages form a particular problem in vacuum tank degassing. In this work, vibration measurements were used for operational state monitoring of gas stirring in vacuum tank degassing. To this end, accelerometers were installed outside the vacuum tank and were used to collect data from 334 vacuum degassing treatments during a time span of 5 weeks. The collected data were then processed and analyzed to study the association of measured vessel vibration with gas injection.

The conclusions of this study can be summarized as follows. Under the conditions of this study, the RMS of the vertical velocity with centered median smoothing using window length of 21 s was found to be the best vibration feature for monitoring gas stirring in a vacuum tank degasser. An LRV was proposed to
quantify the ability of a ladle to generate the maximum amount of vibration with the minimum amount of argon gas. The LRV is defined by a ratio of the cumulated vibration and cumulated argon gas during the vacuum stage. The LRV was found to be useful for revealing abnormal stirrings for each specific ladle. Suitability of the LRV for condition monitoring of the ladle lining was tested, but unfortunately the LRV only has a low correlation with the number of stirrings after partial or full relining of the ladle. Gas leakages in the stirring process can be monitored by a rLRV. In the definition of the rLRV, the approach is equivalent to the LRV with the exception that the rLRV is a vector that consists of ratios of vibration intensity observations and gas flow rate observations collected during the vacuum treatment. In addition to gas leakage monitoring, the rLRV can be used for the online monitoring of the stirring efficiency.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

gas stirring, online monitoring, signal processing, vacuum tank degassing, vibration measurements

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