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# THE MEASUREMENT OF ACOUSTIC EMISSION SIGNALS FROM STEM OF MAIZE UNDER CONTROLLED ENVIRONMENT

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## Abstract

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The present paper focuses on the acoustic emission (AE) measurement method for monitoring of plant transpiration system. AE signals from stem of investigated maize being under well watered condition throughout experiment is investigated with acoustic emission parameters evaluating unit of XEDO-AE system and environmental parameter sensor of XEDO-IO system (Dakel company, Czech Republic) for estimation of xylem cavitation and embolism occurring on stem of plant. After conducting experiment for 4 days, the experimental results indicated that great amounts of AE signals occurred during the daytime, whereas small amounts of AE signals occurred during the night and the variation of all environmental parameter values were associated with the change of AE values interestingly. To clarify the correlation between AE parameter and environmental parameters statistically, multi linear regression was used to describe this correlation. The statistical model showed that the environmental parameters affecting to the variation of an AE parameter value from strongest one to weakest one were air temperature, relative humidity, atmospheric pressure and light intensity at $R^2 = 68.7\%$ and adjusted $R^2 = 68.4\%$. According to these experimental results, using AE method to monitor the investigated plant capable of illustrating the characterization of AE signals generated by plant being under well watered condition. Therefore, from this experiment, AE method could be used to be a tool for detecting whether plant is in well watered condition.

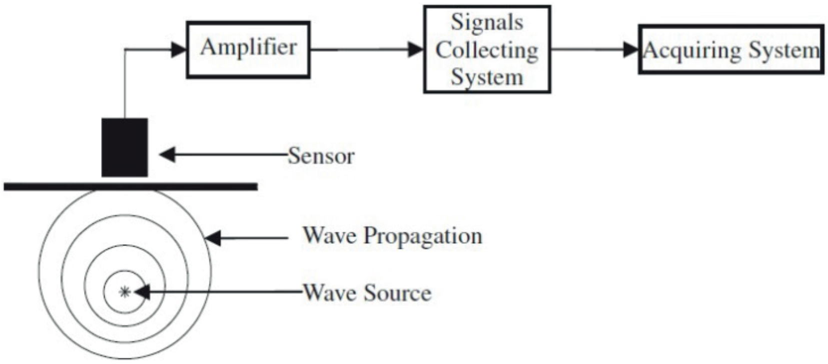
Keywords: acoustic emission, maize, cavitation, plant transpiration system, regression analysis

## INTRODUCTION

Non-destructive testing (NDT) is a wide group of analysis techniques used in science and industry to evaluate the properties of material, component or system without causing damage (Sriwongras *et al.*, 2014). One of these methods is acoustic emission (AE). This technique detects elastic waves generated within a test specimen by such mechanisms as corrosion, plastic deformation, fatigue, and fracture (Dostál *et al.*, 2011).

Generally, AE systems contain sensor, preamplifier, filter, and amplifier, along with measurement, display, and storage equipment. A typical AE detection system is shown in Fig. 1. Suitable sensors are placed on the surface in order to record the transient waves generated by the crack propagation incidents. Subsequently, the characterization and quantification of the damage level could be performed using appropriate AE descriptors.

Studying the transpiration system of plant and tree by using AE method is gradually getting interests from many researchers. The first report from the area of application of audible acoustic emission in the area of plants was published in 1966 by J. A. Milburn and R. P. C. Johns (Černý *et al.*, 2011) and then there are many experiments in AE of plan and trees have been conducted widely in following; Qiu *et al.* (2002) observed the AE of tomato plant and analyzed the relationship between AE and plant water consumption associated with plant transpiration system. They found that the daily patterns of the AE varied depending on the




1: *Diagram of typical AE detection system*

water stress level. AE signals from leaf xylem of both water stressed and well watered potted winter wheat plant were investigated by Xiu-Ling *et al.* (2006). The results of this article described that very few AEs occurred in xylem of wheat leaves in well-watered plant whereas great amounts of AEs have occurred since 5 days of the drought cycle as plant showed obvious leaf curling, indicating significant cavitation in leaf xylem on plant exposed to sever soil water deficit. Jackson *et al.* (1996) explained that AE technique is useful to determine the threshold water potential at which damage to the water-conducting system of the plant but AEs have only a limited use in determining the proportion of embolism in a conducting stem, and other methods are needed to find the percentage reduction in hydraulic conductivity. From publications as mentioned, basically, the occurrence of cavitation in plant transpiration system when plant is under water stress condition can be monitored by using acoustic method. Therefore, it is very interesting to perform more experiment on AE method with transpiration system in order to find the new method how to recognize exactly when the plant want to be watered properly due to its water stress condition.

The aim of investigation was to clarify the relationship between values of AE parameters and the values of environmental parameters from monitoring the transpiration system of investigated plant by using acoustic emission method in order to consider which environmental parameters were the most effect factor to AE parameters. To describe this relationship, statistical analysis was a tool to be used and explained how environmental parameters influence on AE parameters as well as transpiration system of plant.

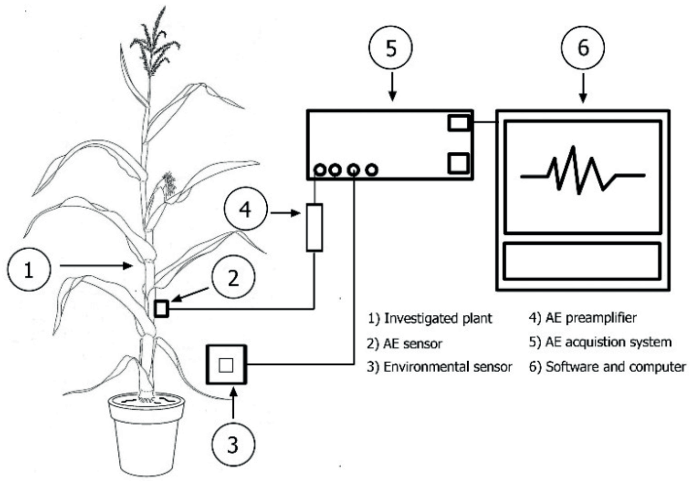
## MATERIALS AND METHODS

### Investigated Plant

In this pilot experiment, one plant has been investigated continuously for 96 hours. Experiment was operated at 9.34 AM from 27$^{th}$–31$^{th}$ March, 2015 at Department of Technology and Automobile Transport and Department of Plant Biology, Faculty of Agronomy, Mendel University in Brno. The investigated plant used in experiment was maize being a variety of Piorun. Sowing an investigated plant took place on 9$^{th}$ February, 2015 by planting it in plastic pot having dimensions 20 cm in height and 25 cm in diameter with substrate (Klasmann TS30), which has structure size of substance around 0–5 mm. Plant was grown in a greenhouse being able to be controlled the environmental factors such as air temperature, light intensity and relative humidity. In order to prevent water stress condition happening on investigated plant during entire experiment, plant was watered one time by tab water of 500 cc before conducting experiment and the top part of plastic pot was covered by aluminium foil sheet in order to protect the water loss from soil surface to air due to evaluation.

### Experimental Procedure and Measurement

To implement experiment, acoustic emission device was used to detect the AE signals generated from the stem of an investigated plant in order to estimate the situation of its transpiration system. A schematic diagram of the experimental set-up as displayed in Fig. 2 comprises investigated plant grown in plant pot, broadband AE sensor with a metal waveguide, environmental monitoring sensor, AE preamplifier, AE acquisition system, AE software and computer. The process of measuring the plant using this device can be described as follows; First, AE sensor having operating frequency of 25–60 kHz manufactured by Dakel firm (Czech Republic) was placed on the waveguide to receive AE signals generated by tested plant properly (Sriwongras *et al.*, 2015). The waveguide was a signal connector that has function of transferring AE signal from investigated plant to AE sensor. The used waveguide in this experiment was drawing pin made of stainless steel. One side of waveguide was conical tip inserted into the stem of investigated plant and another side was thin round shape used for connecting with an AE sensor. To improve AE signals, the AE preamplifier of 35 dB was used to magnify the received signals before these signals were converted from analog signals to digital signals by AE acquisition unit. In the meantime of conducting experiment, environmental monitoring




2: *Setting up AE equipment with an investigated maize*

sensor (EMS) was employed to record the data of air temperature, relative humidity and light intensity in order to find the relationship between environmental parameters and AE parameters. Finally, all digital signals were analyzed and shown the results of all data by computer programs being Daemon and Deashow developed by Dakel frim (Czech Republic).

### Statistical Measurement

Finding the relationship between AE parameter and environmental parameters statistically, regression analysis methods was conducted to describe which environmental parameters were significant to affect to AE parameter that was root mean square (RMS). In statistics, regression analysis is a methodology for evaluating a functional relationship among response or dependent variables and predictor or independent variables. When considering only one response variable with one predictor variable, the regression analysis is named simple linear regression; while when considering one response variable with more predictor variables, the regression is called multiple linear regression.

### Simple Linear Regression

The simple linear regression has an equation of the form (Fumo *et al.*, 2015)

$$Y = \beta_0 + \beta_1 X + \varepsilon, \tag{1}$$

where $Y$ is the response variable, $X$ is the predictor variable, $\beta_0$ and $\beta_1$ are the regression coefficients or regression parameters, and $\varepsilon$ is an error to explain the discrepancy between predicted data from Eq. (1) and the observed data. The predicted value form of Eq. (1) is

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X, \tag{2}$$

where $\hat{Y}$ is the predicted value and $\hat{\beta}_0$ and $\hat{\beta}_1$ are estimates of the regression coefficients.

### Multiple Linear Regression

The multiple linear regression is the generalization of the simple linear regression model. The model in multiple linear regression allows more than one predictor variable.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p + \varepsilon, \tag{3}$$

where $Y$ is the response variable, $X_1, X_2, \ldots, X_p$ are the predictor variables with p as the number of variables, $\beta_0, \beta_1, \ldots, \beta_p$ are the regression coefficients, and $\varepsilon$ is an error to account for the discrepancy between predicted data and the observed data. The predicted value form of Eq. (3) is

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 X_1 + \hat{\beta}_2 X_2 + \ldots + \hat{\beta}_p X_p, \tag{4}$$

where $\hat{Y}$ is the predicted value and $\hat{\beta}_1, \hat{\beta}_2, \ldots, \hat{\beta}_p$ are estimates of the regression coefficients.

### Quality of Regression Analysis

The statistical measure that show how close the data are to fit the regression line is the coefficient of determination ($R^2$) as shown in Eq. (5), or the coefficient of multiple determination for multiple regression (The minitab, 2013).

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \overline{y})^2}, \tag{5}$$

where $\Sigma(y_i - \hat{y}_i)^2$ and $\Sigma(y_i - \overline{y})^2$ are called sum of squared errors (SSE) and total sum of squares (SST), correspondingly.

The value of $R^2$ varies between 0 and 1; a value of $R^2 = 0.9$ indicates that 90% of the total variability in the response variable is accounted for by the predictor variables. However, a large value of $R^2$ does not necessarily mean that the model fits the data well. Thus, a more detailed analysis is needed to ensure that the model can satisfactorily be used to describe the observed data and predict the response for another set of data different from the one used to generate the model. The value used to check the regression model other than $R^2$ is adjusted $R^2$ (Statistics how to, 2015) as shown in Eq. (6).

$$R^2_{adj} = 1 - \left[\frac{(1-R^2)(n-1)}{n-k-1}\right], \quad (6)$$

where $n$ is the number of points in data sample, $k$ is the number of variables in your model.

The root mean square error (RMSE) of the model is another parameter to evaluate the quality of the fitting, which is a measure of the scatter in the data around the model. The RMS for a simple linear model is computed as displayed in Eq. (7) (Fumo *et al.*, 2015).

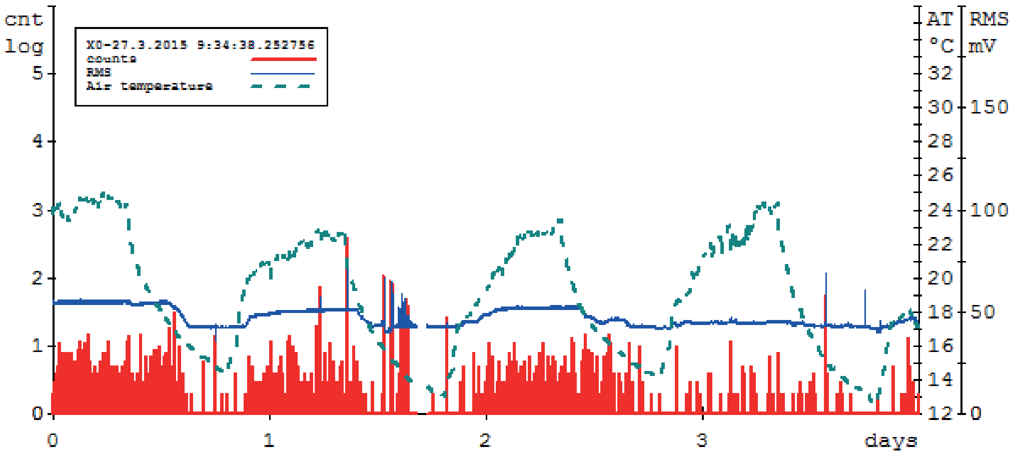
$$RMSE = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n}} = \sqrt{\sum\frac{(Y-\hat{Y})^2}{n}}, \quad (7)$$

And for a multiple linear model is calculated as displayed in Eq. (8)

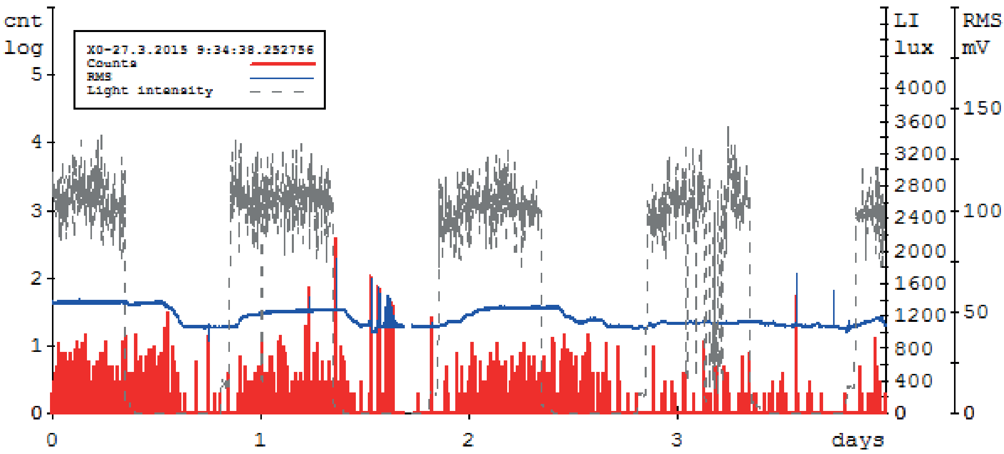
$$RMSE = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-k}} = \sqrt{\sum\frac{(Y-\hat{Y})^2}{n-k}}. \quad (8)$$

## RESULTS

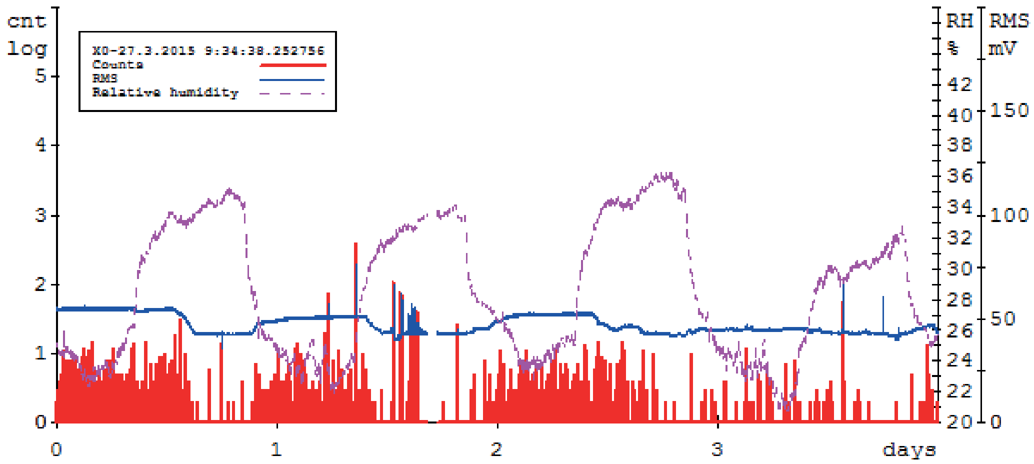
The experimental results of relationship between the values of AE parameters and the values of environmental parameters throughout four days in this experiment can be represented as line graphs in Figs. 3–6. In these line graphs, the considered AE parameters consist of the root mean square (RMS) which is indicative of average acoustic emission energy and the number of counts which is the number of signals crosses a preset threshold (Miller *et al.*, 2005). For environmental parameters, the values of air temperature (AT), light intensity (LI), relative humidity (RH) and atmospheric pressure (AP) were recorded. According to the experimental results, they showed that there were two possible patterns of line graph in this experiment; first pattern was that values of RMS and the number of counts mostly varied directly with values of air temperature, light intensity and atmospheric



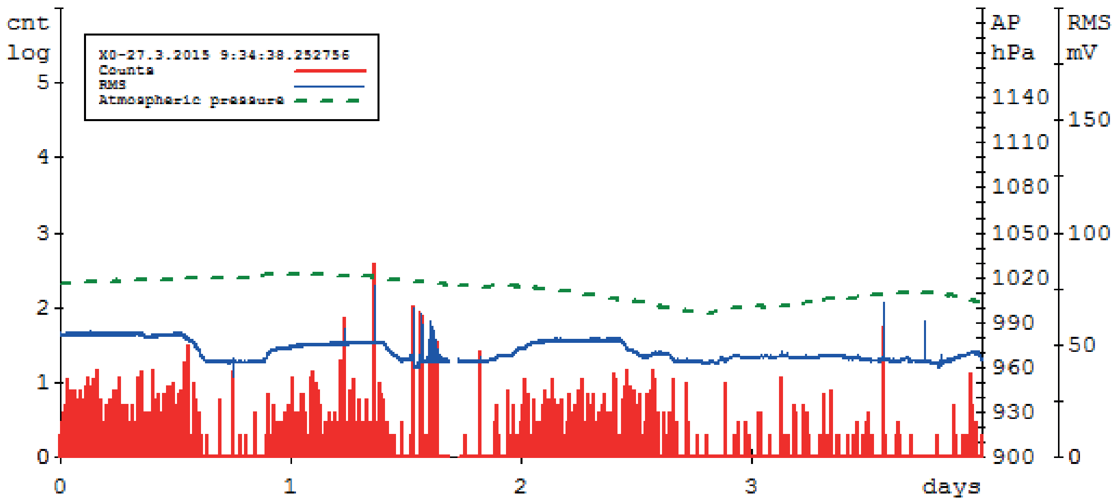

3: *AE parameters (RMS and the number of counts) and air temperature versus time during measurement*




4: *AE parameters (RMS and the number of counts) and light intensity versus time during measurement*




5: *AE parameters (RMS and the number of counts) and relative humidity versus time during measurement*




6: *AE parameters (RMS and the number of counts) and atmospheric pressure versus time during measurement*

I: *Statistical values of multiple linear regression in this experiment throughout 4 days*

| Independent variable | Coefficient | Standard error for coefficient | T-value | P-value |
|---|---|---|---|---|
| Constant | –171.41 | 13.63 | –12.58 | 0.000 |
| Air temperature (AT) | 1.3938 | 0.0581 | 23.98 | 0.000 |
| Light intensity (LI) | –0.0003 | 0.0001 | –2.21 | 0.028 |
| Relative humidity (RH) | 0.4746 | 0.0551 | 8.62 | 0.000 |
| Atmospheric pressure (AP) | 0.1769 | 0.0134 | 13.22 | 0.000 |

II: *Quality values of multiple linear regression in this experiment throughout 4 days*

| S (standard error) | $R^2$ (coefficient of determination) | Adjusted $R^2$ |
|---|---|---|
| 2.4152 | 68.7% | 68.4% |

pressure as illustrated in Figs. 3, 4, 6. Second pattern was that values of AE parameters mostly varied inversely with relative humidity values as displayed in Fig. 5.

Multiple linear regression showing in Eq. (9) describe the statistical relationship between dependent variable which is RMS and independent variables which are all recorded environmental parameters. From Eq. (9), it was found that values of regression coefficient of constant, air temperature, light intensity, relative humidity and atmospheric pressure were equal to –171.41, 1.3938, –0.0003, 0.4746 and 0.1769, respectively. Tab. I listed the p-value of all independent variables indicates that all independent variables have their p-value less than 0.05 and Tab. II representing the quality values of multiple linear regression shows that the value of standard error (S) is 2.4152 and coefficient of determination ($R^2$), Adjusted $R^2$ are equal to 68.7 and 68.4, respectively.

$$RMS = -171.41 + 1.3938AT - 0.0003LH + 0.4746RH + 0.1769AP. \quad (9)$$

## DISCUSSION

From the experimental results using acoustic emission method to measure AE signals generated from stem of investigated maize, the results showed that the parameters of AE signal were varied according to the value of air temperature, light intensity, relative humidity and atmospheric pressure throughout 4 days without water stress condition occurring in tested plant. Therefore, the change of value of AE parameters during measurement was likely to interpret the movement of water inside the stem of investigated plant. This experimental result was consistent with the other researches, for instance, Černý *et al.* (2011) justified that the change of acoustic emission activity roughly corresponds to the day cycles and it was evident that the AE signals was more active in the early-evening and partially in the early morning periods. Zweifel *et al.* (2005) reported that ultrasonic acoustic emission in trees was often related to collapsing water columns in the flow path as a result of tensions called cavitation. According to multiple linear regression as shown in Eq. (9), this statistical model indicated that all environmental parameters were associated with the change of RMS value because of the fact that the p-value of all environmental parameters were less than 0.05 and the values of regression coefficient in Eq. (9) demonstrated that the environmental parameters influencing to the value of RMS value from strongest one to weakest one were air temperature, relative humidity, atmospheric pressure and light intensity, respectively. Moreover, the quality values of multiple linear regression listed in Tab. II presented that the values of $R^2$, adjusted $R^2$ were not too different in each other and their values were in the quite high level. Therefore, this statistical model capable of describing that the variability of RMS value generated from stem of plant depends on the values of environment parameters fairly.

## CONCLUSION

The implementation of the acoustic emission method for passive monitoring in plant transpiration system hold a great promise for process understanding and potential recognizable system on water stress condition of plant. From using AE sensor with waveguide to receive signals at stem of investigated plant, the experimental results showed that both values of AE parameters and values of environmental parameters have correlation together interestingly throughout experiment. From its correlation, the change of values of AE parameters would occur from the response of transpiration system of plant due to variation of environmental parameters. Therefore, the values of AE parameters can describe the situation of transpiration system in plant properly. Furthermore, in this experiment, multiple linear regression was used to figure out statistical relationship between the value of RMS and the values of environmental parameter. The final statistical model showed that the values of environmental parameters influence on the variability of RMS value moderately.

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