UNCERTAINTY CALCULATION PROCEDURES IN VIBRATION MEASUREMENT IN ROTATING MACHINES OF ELECTRIC ENERGY GENERATION

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Abstract. *Vibrations in rotating machines used in electric energy generation are normally undesirable, for causing noise, performance reduction and damage, which can provoke the quality reduction of electric energy supplied. In order to minimize the effect of these problems it is important to realize the vibration monitoring of these machines, to allow the accomplishment of a high efficiency predictive maintenance. Due to the importance of monitoring, it is necessary the uncertainty calculation associated with the vibration measurement parameters, in order to get a statistical reliability. In this paper, an uncertainty calculation method in vibration measurement is presented, based on values obtained by the measurement system which includes accelerometer, signal conditioner system, data acquisition device and computer. The calculated and stored uncertainty values are presented to the operator, in real time, by a graphical interface at computer screen. The obtained results allow a better definition of maintenance project and, consequently, increase the time of operational life of this machine.*

Keywords*: Vibration, Measurement, Uncertainty, Acceleration.*

1. INTRODUCTION

For companies where rotating machines participate in some production process, the quality of that production will depend, among others factors, of these machines efficiency. Seeking to guarantee a regularity of that efficiency, it is necessary to exist a machine components predictive maintenance.

The predictive maintenance is a procedure that helps to prevent the equipments or systems flaws through attendance of several parameters, allowing the equipment continuous operation for the largest possible time (Nepomuceno, 1989).

The vibration monitoring is considered indispensable in any system of predictive maintenance of rotative machines. In industrial plants, the eventual necessity to select equipments for a vibrations monitoring program should consider, over all, the equipment importance for the production and its maintenance cost.

As the existence of vibratory elements in a rotative machine produces undesirable effects, such as, precocious failures of vital pieces and damages in the structure (Kather, 1998), taking to the inefficiency of the production, a vibration parameters monitoring should be made. That monitoring allows the correction of problems by verification of origin of the flaws, in case they happen at the material, at equipment or at operators, guaranteeing, thus, the machine operation with efficiency and quality for a larger time, or in accordance with its operational life (Nepomuceno, 1989).

In order to increase the reliability in vibration measurement in rotative machines, it is presented in this article the development of a procedure of uncertainty calculation in vibration measurement, implemented by the platform LabView. With this method, the predictive maintenance earns in reliability and agility on its execution, once the result of vibration monitoring is supplied in real-time to the operator.

2. MEASUREMENT SYSTEM DESCRIPTION

At the system shown in Fig. 1, the measurement procedure consists of converting the acceleration, generated by a vibration source (to simulate the rotative machine vibration, a device denominated "shaker" has been used) in voltage signal, using a sensor/transducer (accelerometer). It will also be used a signal conditioner device that will filter and amplify the sensor output signal, adapting it, thus, to the specifications of the data acquisition device. This device is responsible for the analogical-digital conversion on the way that readings, registrations, calculations and reports, referring to the measurement, can be made in a microcomputer using the platform LabView.

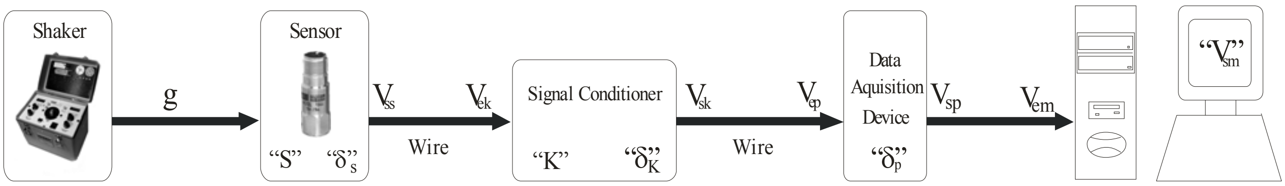

Figure 1. Vibration measurement system.

For that system, a mathematical model has been determined, by consideration of the involved variables, and it will be used for the uncertainty calculation in vibration measurement. The procedure to determine that model is described on the next section.

2.1. Determination of mathematical model for the uncertainty calculation.

The procedure accomplished to determine the mathematical model will consider the acceleration as a function of other variables which will be determined. It is important to stand out that, in this mathematical modeling, errors in voltage, provoked by wires imperfections that connect the measurement system elements shown in Fig. 1, have been rejected. It has been admitted that these errors are very small compared with the errors provoked by the other system components

Thus, the accelerometer output voltage (V_{ss}) relates with the input acceleration (g) by the following form:

$$V_{SS} = S.g \tag{1}$$

Where "S" represents the sensor sensitivity (in mV/g). The sensor will supply voltage values with larger accuracy after its calibration, of which will be obtained the certificate containing the value of accuracy error, represented by δ_s. With this error, Eq. (1) can be rewrite in the following way:

$$V_{SS} = (S - \delta_S).g \tag{2}$$

In the conditioner output the voltage signal will be amplified by a gain (K), which can have its value corrected after calibration. The Eq. (3), shown below, relates the conditioner output voltage (V_{sk}) with the gain K, corrected by a factor δ_K.

$$V_{SK} = (S - \delta_S).g.(K - \delta_K) \tag{3}$$

The signal conditioner output voltage can be considered equal to the data acquisition device input voltage. After calibration, the output voltage value (V_{sp}) can be corrected subtracting its calibration error δ_p, as it is shown in Eq. (4).

$$V_{SP} = [(S - \delta_S).g.(K - \delta_K)] - \delta_P \tag{4}$$

The microcomputer input voltage will be considered equal to the data acquisition device output voltage and, finally, they are also considered equal the input and output microcomputer voltage, being despised its accuracy error. Consequently, the microcomputer output voltage (V_{SM}) assumes the same data acquisition device output voltage value expressed by Eq. (4). After those considerations, the model for calculate "g" will be expressed in the following way:

$$g = \frac{V_{SM} + \delta_P}{(S - \delta_S).(K - \delta_K)} \tag{5}$$

For an estimate of "g", the model variables will assume values in agreement with the following criteria.

In the random variable case, where a sample of identical and independent measurements were accomplished, the value of its arithmetic average has been attributed. In the case of the variables for which a probability distribution was admitted *a priori*, the values of their expectations were attributed (BIPM, 2003).

The accelerometer sensitivity value (S) is 100 mV/g (Wilcoxon, 2007). For the signal conditioner gain (K), there are three possibilities: 10, 50 and 100. The calibration certificate of this conditioner, or of any other, it should show a calibration error for each gain value or an error that is applied at all gains, besides its uncertainty.

2.2. Input variables uncertainties combination

After determining the model, according to Eq. (5), the measurement uncertainty will be calculated in agreement with BIPM (2003), where the uncertainties are combined in the following way:

$$u_c(g) = \sqrt{c_{Vsm}^2.u^2(V_{SM}) + c_{\delta p}^2.u^2(\delta_P) + c_{\delta k}^2.u^2(\delta_K) + c_{\delta s}^2.u^2(\delta_S)} \tag{6}$$

Where u_c (g) is the combined standard uncertainty, the terms $u^2(.)$ are the standard uncertainties of the input variables and C_i's are the sensitivity coefficients of the respective input variables, whose calculations are made by following way:

$$c_{Vsm} = \frac{\partial g}{\partial V_{SM}} = \frac{1}{(S - \delta_S).(K - \delta_K)} \tag{7}$$

$$c_{\delta_K} = \frac{\partial g}{\partial \delta_K} = \frac{V_{SM} + \delta_P}{(S - \delta_S).(K - \delta_K)^2} \tag{8}$$

$$c_{\delta_S} = \frac{\partial g}{\partial \delta_S} = \frac{V_{SM} + \delta_P}{(S - \delta_S)^2.(K - \delta_K)} \tag{9}$$

$$c_{\delta p} = \frac{\partial g}{\partial \delta_P} = \frac{1}{(S - \delta_S).(K - \delta_K)} \tag{10}$$

Values of "S" and "K" do not represent random variables but constants (declared by manufacturers). For this reason, they do not consist in the uncertainties combination. Table 1 show the calculation form for each one of them:

Table 1. Uncertainties calculation table

Variable	Probability distribution	Standard uncertainty
microcomputer output voltage	Normal	$S_X / \sqrt{N}$
Data acquisition device calibration error	Normal (after calibration)	U/k
Accelerometer calibration error	Normal (after calibration)	Same to the previous
Signal conditioner calibration error	Normal (after calibration)	Same to the previous
(U) Expanded uncertainty; (k) Coverage factor. Both should be informed in calibration certificate		

The term "S", in the computer output voltage standard error expression, is the standard deviation of the readings, which can be calculated using Eq. (11), where each X_i is a sample value and $\overline{X}$ is the arithmetic average of X_i's:

$$S = \sqrt{\frac{\sum_{i=1}^{N}(X_i - \overline{X})^2}{N - 1}} \tag{11}$$

If the coverage factor "k", informed at Tab. 1, referring to variables uncertainty calculation, do not be declared at calibration certificate, it should try to observe if the level of confidence and the degrees of freedom are registered. Therefore, with these values, the distribution t table can be consulted and obtained "k" value. The coverage factor supplies the interval, around an estimate percentage, of chance of containing the true value of "g".

As last procedure step, the calculation of expanded uncertainty of measurement will be given by the product between the combined uncertainty u_c (g) and the coverage factor $k_{95,45\%}$ shown in Eq. (12).

$$U = k_{95\%}.u_c(g) \tag{12}$$

The "k" value should be observed at distribution t table (BIPM, August 2003) for a level of confidence of 95,45% and V_{eff} degrees of freedom, where V_{eff} is calculated by the following way:

$$V_{eff} = \frac{U_c^4(g)}{\sum_{i=1}^{M} \frac{(c_i.u(X_i))^4}{v_i}} \tag{13}$$

In Equation (13) X_i's are the input variables, whereas V_i's are degrees of freedom for each one of them, which are determined deducting an unit of the sample size. However, for variables whose estimate of the standard uncertainty has been obtained by calibration certificate, the degree of freedom is infinite, because the probability distribution is known (BIPM, 2003).

If the result of Eq. (14) exceeds the last contained value of degrees of freedom at distribution t table, the value corresponding to infinites degrees of freedom should be used as coverage factor.

And finally the measurement result will be told as in Eq. (15).

$$g \pm U \tag{14}$$

3. PROCEDURES OF UNCERTAINTY CALCULATION IN VIBRATION MEASUREMENT

The instrumentation, represented by the block diagram shown in Fig. 1, was used to measure the acceleration provoked by an electrodynamic vibrator or shaker (Instruments, 2007). It was adjusted in shaker a frequency of 120 Hz and an acceleration value of 0,1g. After the system be placed in operation, routines in LabView had been used for register 5.000 curve points (approximately a sinusoide), which made possible to analyze 120 periods and, thus, 120 values of maximum (any other characteristic value of a period can be used for the calculation). These data are listed below (in mV) jointly with a line graph to visualize its behavior.

Table 1. Table containing the sample of 120 V_{SM} amplitude values.

436,917	440,579	440,172	452,176	435,086	444,852	440,579	449,734	432,645	447,293	435,086	450,345
438,138	449,938	441,067	444,974	444,974	445,950	435,086	449,938	435,289	449,734	445,462	443,021
435,289	450,833	439,969	445,055	442,410	449,938	435,696	452,176	440,172	450,345	437,527	454,821
445,950	445,055	430,407	456,448	444,852	446,683	447,903	445,055	445,462	449,938	430,407	450,833
444,852	449,938	440,579	447,903	440,579	447,293	449,938	451,565	448,514	449,938	436,185	454,617
441,189	447,293	449,938	455,838	440,172	449,734	441,800	444,852	449,938	456,448	439,969	446,683
447,293	449,938	440,579	454,617	441,800	456,448	449,938	446,072	445,055	446,683	446,683	452,176
440,172	449,938	445,055	456,448	427,762	454,617	446,072	440,172	446,683	456,448	430,203	450,345
445,055	452,176	441,800	454,617	445,055	446,072	444,852	446,683	446,072	449,734	441,800	456,448
445,055	450,345	449,734	446,072	441,800	461,331	446,072	449,734	451,565	457,059	435,086	459,703

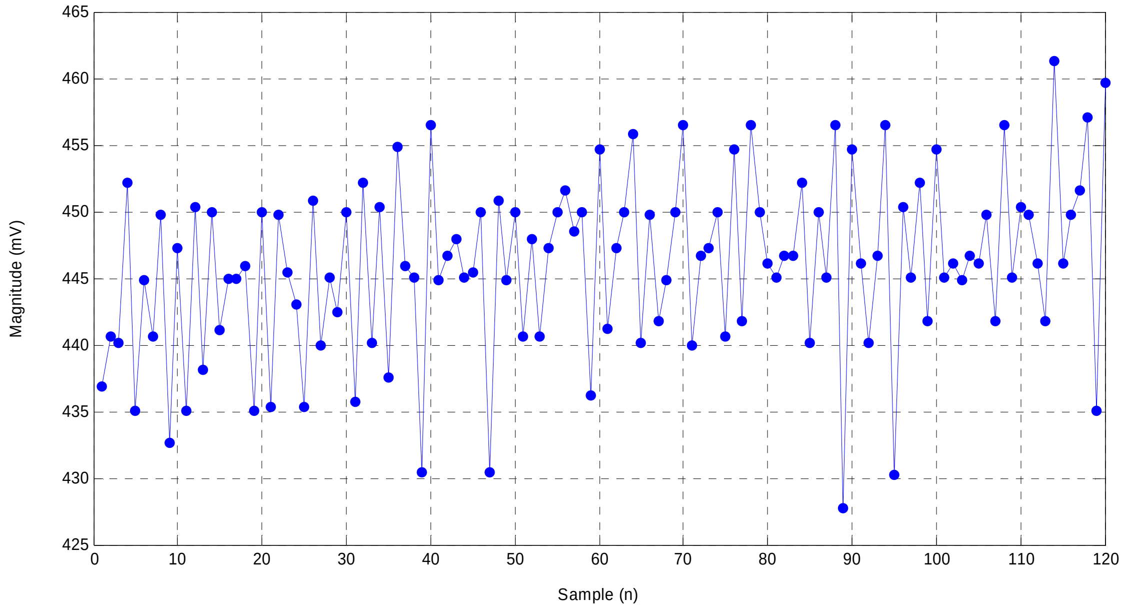

Figure 1. Graph of measured values (voltage peaks)

3.1. Calculation description of the average estimates and standard uncertainty

On the next sections some analyses and statistical considerations about the average and the standard uncertainty will be listed, for each variable involved in the mathematical model shown in Eq. (5).

3.1.1. Voltage read at microcomputer screen (V_{sm})

The arithmetic mean of the 120 peak values gives the estimate to them for the average of this variable where the calculated value was of 445,942 mV. Applying the Tab. 1 equation, the estimate for the standard uncertainty resulted in 40,708 mV.

3.1.2. Data acquisition device calibration error (δ_p)

Data contained in Instruments (2006) inform that error bounds for the data acquisition device model are ±0,112 mV. Due to the lack of data acquisition device calibration, it is consider a rectangular distribution for this variable defined in the interval ±0,112 mV, resulting in null mean and standard uncertainty equal to 40,064 mV.

3.1.3. Signal conditioner calibration error (δ_k)

For this calculus simulation a value of ±10% was stipulated on the conditioner gain. The gain value used was 50. The error bounds for this variable, then, are ±5. Accepting a rectangular distribution, the average is zero and the standard uncertainty is 2,886.

3.1.4. Sensor calibration error (δ_s)

The sensor datasheet contain the value ± 20% of variation. Therefore, for a sensitivity of 100 mV/g, this variable can assume any value between 80 and 120 mV/g. It was admitted that this error distributes itself uniformly inside the interval of 80 e 120 mV/g . Thus, the average and the standard uncertainty are, respectively, zero and 11,547 mV/g.

3.2. Calculation of combined standard uncertainty

Applying the equations mentioned in chapter 2 (from Eq. (5) to Eq. (14)), with the considerations mentioned on item 3.1, it was possible to get the results shown in Tab. 2.

Table 2. Calculation results of uncertainty of measurement.

Input Variables	Estimates	Sensitivity coefficients	Standard uncertainty	Contribution to uncertainty	Degrees of freedom
Vsm	445,942758	0,000200	0,605505	0,000121	119,000000
δp	0,000000	-0,000200	1,789786	-0,000358	infinite
K_1	100,000000				
δk_1	0,000000	-0,000892	11,547005	-0,010299	infinite
K_2	50,000000				
δk_2	0,000000	-0,001784	2,886751	-0,005149	infinite
Measurand (g)	0,089189	**Combined uncertainty**		0,011520	infinite
		Coverage factor:		k = 2	
		Expanded uncertainty		0,023041	

The effective degrees of freedom, calculated in accordance with Eq. (13), resulted in a large number (9.745.946.770), in consequence of a small contribution for uncertainty, proceeding from a type A evaluation, in relation to the proceeding from type B evaluation. Thus, the value for this degree of freedom was considered as infinite.

The g estimate is found substituting the input variable values by its respective estimates as follow:

$$g = \frac{V_{SM} + \delta_P}{(S - \delta_S).(K - \delta_K)} = \frac{445{,}942758 + 0}{(100 - 0).(50 - 0)} = 0{,}089189 \text{ g} \quad (15)$$

Finally the complete measurement result can be express as:

$$G = 0{,}089189 \pm 0{,}023041 \quad (16)$$

Or on interval form:

$$G \in [0{,}066148 \,;\, 0{,}112229] \quad (17)$$

4. INSERTION OF UNCERTAINTY CALCULATION PROCEDURE IN LABVIEW PLATFORM

As it has been considered in this paper, it is necessary to insert the uncertainty calculation procedure as a calculation routine at LabView platform. The objective is to calculate, in real time, the measurement uncertainty values and later show them at computer screen together with the expected value of measured quantity.

In order to these values be shown, it is necessary to construct sub-routines or SubVI' s that execute the same mathematical procedure shown on chapter 2. On the next section, it will be shown the subvi's architecture.

4.1. Programming in Labview

Programs created in LabVIEW are called virtual instruments, or VI's, due to the similarities of appearance and operation with real instruments, such as oscilloscopes and multimeters. A VI within another VI receives the denomination of subVI. A subVI corresponds to a subroutine in text-based programming languages (Instruments, 2004). Both (VI and subVI) are formed by the following components: front panel, block diagram, an icon and a panel with input and output connections. The block diagram for uncertainty measurement calculation is illustrated in Fig. 2.

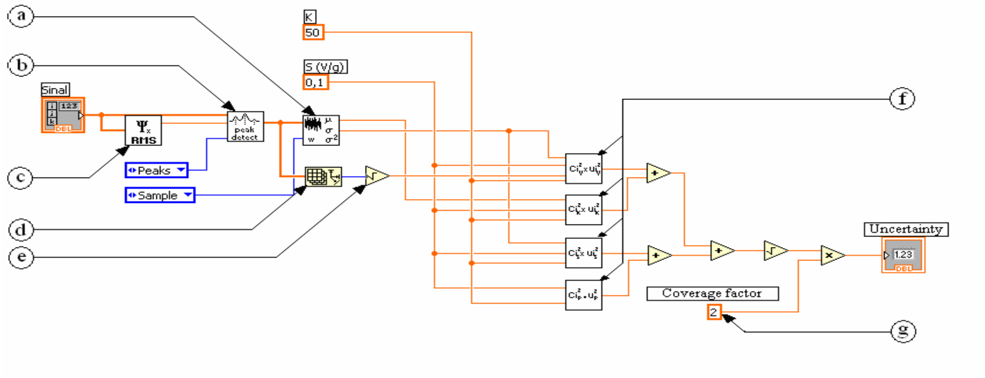

Figure 2. (a) Block for average and standard deviation calculation of points set. (b) Peaks detector (c) Block that calculate RMS value (d) Block that supplies the number of input vector points (e) Function square root (f) subVI' s (V_{sm}) (g) coverage factor.

The corresponding signal sample points pass through peak detector (b). That block detects the maximum or minimum values, starting from a threshold defined by user. As value for this threshold, the RMS signal value has been adopted, due to the fact of this value is closer of real maximum than average value, minimizing, thus, the possibility of error. The block indicated in (a) calculates the average and the standard deviation, which serves as input parameters for next subVI' s. The block (d) supplies at its output the number of input vector points, whereas the positive square root of this value is extracted by the block (e).

The quantity shown by V_{sm} corresponds to coverage factor “k”, which is used to expanded uncertainty determination. The “k” value is observed of the distribution t table in accordance with the number of effective degrees of freedom and the level of confidence (95.45%). For simplicity, the “k” value equal 2 was used, in view the fact of rarely occurs values lesser than 100 for effective degrees of freedom. Therefore, for this work, “k” equal 2 was adopted.

4.2. SubVI' s that composes the uncertainty calculation process

It is important to detach that Eq. (7), Eq. (8), Eq. (9) and Eq. (10), which had been written in LabView, are respecting the fact that the model variables had been substituted by its respective means, determined from the probability distribution admitted *a priori* (rectangular distribution). Therefore, the expected values for each one of them are E (δp) = E (δk) = E (δs) = 0.

The blocks diagram for product calculation between the sensitivity coefficient square (c_i^2), and the uncertainty contribution square (u_i^2), for V_{sm} variable is shown in Fig. 3.

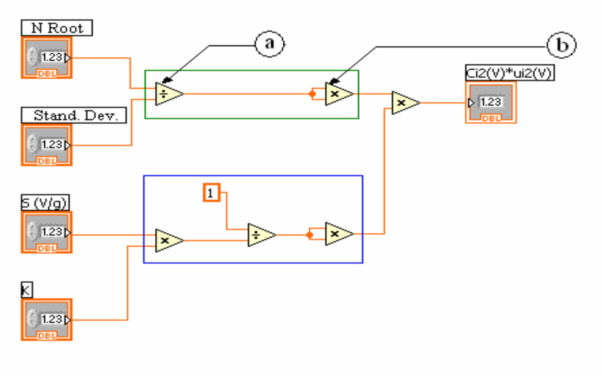

Figure 3. SubVI blocks diagram that calculates c_i^2 (V_{sm}) x u_i^2 (V_{sm}): (a) Function division (b) Function multiplication, with the two inputs at the same point in order to effect the square operation.

The input parameters of this subVI are the standard deviation, the positive root square of the samples number, the sensor sensitivity and the conditioner gain. The standard uncertainty for V_{SM} variable, as already mentioned, is given by $S/\sqrt{N}$. The green rectangle detaches the function that carries through the calculation of this uncertainty and raises it to square. The blue rectangle shows the functions that make the sensitivity coefficient calculation, given by Eq. (7).

As the same way, in Fig. 4, 5 and 6 are detached, by the green rectangle, the sensitivity coefficient calculation for the components K, S and V_p, respectively. The components contributions for the combined standard uncertainty are shown by the blue rectangle.

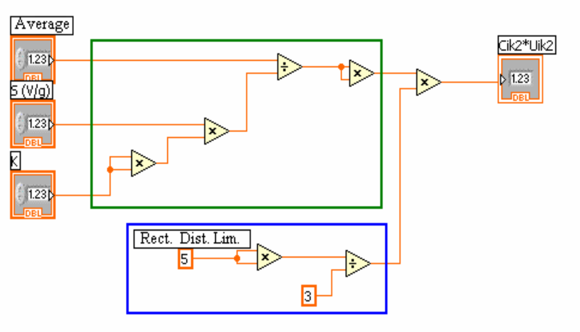

Figure 4. SubVI block diagram which calculates $c_i^2(K).u_i^2(K)$.

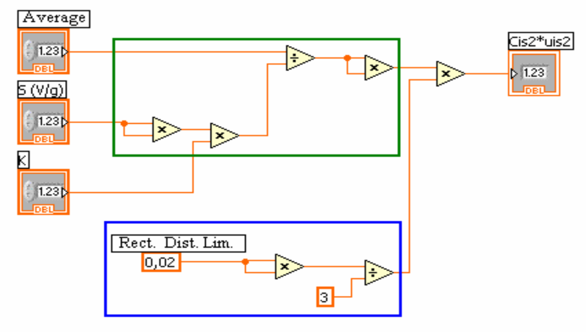

Figure 5. SubVI blocks diagram which calculates $c_i^2(S).u_i^2(S)$.

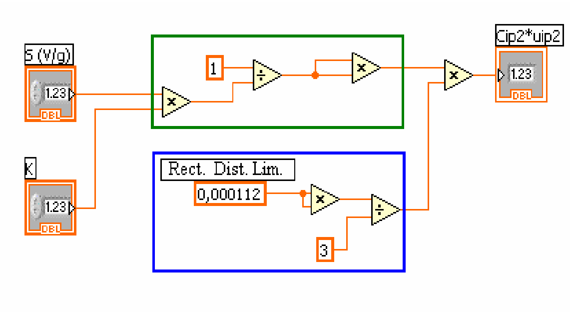

Figure 6. SubVI blocks diagram which calculates $c_i^2(Vp).u_i^2(Vp)$.

5. CONCLUSIONS

In accordance with statistical results analysis it has been observed that it is possible evaluate the vibration measurement reliability through its uncertainty calculation, using a data acquisition device and a monitoring software.

In order to elaborate the optimum possible mathematical model to express the system uncertainty of vibration measurement it is necessary to know the maximum error contributions of each one system components.

In this work, good results has been gotten using the data acquisition device calibration errors, the conditioner gain error and the sensor calibration error. However, uncertainty calculation becomes more realistic when new error contributions are introduced which can be identified in the system.

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