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Development of a New Data Processing System for Increasing the Accuracy of a Levitation Mass Method (LMM) based Measurement

Eko Satria[1*], Hendro[2], Mitra Djamal[1,2]

[1] Department of Physics, Institut Teknologi Sumatera, Lampung, Indonesia
[2] Department of Physics, Institut Teknologi Bandung, Bandung, Indonesia

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Corresponding author: eko.satria@fi.itera.ac.id

ABSTRAK

Levitation Mass Method (LMM) adalah metode sebagai penguji material untuk mengevaluasi respon mekanis benda terhadap gaya tumbukan. Dalam metode ini, massa dibuat bertabrakan dengan material yang akan diuji dan impuls, yaitu integrasi waktu gaya tumbukan, diukur dengan sangat akurat sebagai perubahan momentum massa. Untuk merealisasikan gerakan linier dengan gesekan yang cukup kecil yang bekerja pada massa, digunakan bantalan linier pneumatik. Gaya inersia yang bekerja pada massa dihitung dari kecepatan massa. Kecepatan ditentukan sangat akurat dengan cara mengukur frekuensi pergeseran Doppler dari sinar laser yang dipantulkan pada massa menggunakan interferometer optik. Untuk menentukan pergeseran frekuensi Doppler untuk pengolahan data LMM diperlukan metode estimasi frekuensi. Beberapa metode telah dikembangkan untuk mengestimasi frekuensi pemrosesan data LMM dengan akurasi tinggi, yaitu Zero-Crossing Average Method (ZAM), Zero-Crossing Fitting Method (ZFM), Sine Wave Fitting, dan Zero-crossing Sine Wave Fitting. Semua metode direalisasikan menggunakan zero crossing dari bentuk gelombang yang diperoleh dari digitizer. Metode yang lebih baik untuk mengestimasi frekuensi pada bentuk gelombang digital akan memungkinkan presisi yang lebih tinggi untuk hasil yang lebih akurat. Dalam penelitian ini telah dikembangkan metode baru yang dapat meningkatkan akurasi. Program dikembangkan dengan menggunakan segmentasi data untuk mendapatkan frekuensi bentuk gelombang digital. Program yang dikembangkan memiliki error terkecil (1.98×10^{-10} untuk N = 200) dibandingkan dengan metode lainnya (2,31 x 10-3 untuk ZAM; 1,10 x 10-3 untuk ZFM; dan 8,69 x 10- 4 Zero-crossing Sine Wave Fitting).

Kata kunci: C#, estimasi frekuansi, levitation mass method, visual studio, zero crossing.

ABSTRACT

Levitation Mass Method (LMM) is the method as a material tester to evaluate the mechanical response of general objects against impact forces. In this method, a mass is made to collide with material to be tested and the impulse, i.e. the time integration of the impact force, is measured highly accurately as a change in momentum of the mass. To realize linear motion with sufficiently small friction acting on the mass, a pneumatic linear bearing is used. The inertial force acting on the mass is calculated from the velocity of the mass. The velocity is determined, highly accurately by means of measuring the Doppler shift frequency of a laser light beam reflected on the mass using an optical interferometer. To determine the Doppler frequency shift for LMM data processing, the method for estimating the frequency is necessary. Several methods have been developed to estimate the frequency for the LMM data processing with high accuracy, i.e. Zero-Crossing Average Method (ZAM), Zero-Crossing Fitting Method (ZFM), Sine Wave Fitting, and Zero-crossing Sine Wave Fitting. All methods realized using zero-crossing point of the waveform obtained from digitizer. A better method to estimate frequency on the digitized waveform will enable higher precision for a more accurate result. In this research, a new method which can improve the accuracy has been developed. The program was developed using data segmentation to obtain the frequency of digitized wave form. The developed program has the smallest error (1.98×10^{-10} for N= 200) compare to other methods (2,31 x 10^{-3} for ZAM; 1,10 x 10^{-3} for ZFM; and 8,69 x 10^{-4} for Zero-crossing Sine Wave Fitting).

Keywords: C#, frequency estimation, levitation mass method, visual studio, zero crossing.

1. Introduction

Mechanical parameter measurement of materials is very necessary for material testing and characterization [1]–[4]. In general, the measurement of mechanical parameters can be divided into two categories: static measurement conditions using a stationary load, and measurement of the dynamic conditions using a moving load [5], [6]. The need to measure and evaluate the mechanical parameters of materials in dynamic conditions also increased in industrial and research applications such as material testing, motion control, and crash testing [7], [8]. In this application, the force acting on the material to be tested was measured using force transducer, and the position of the point subjected to force is measured using a position transducer.

At this time, there is no standard method for evaluating the dynamic characteristics of a force transducer [5], [7], [9]. Force transducer is usually calibrated by a standard method using a static load condition. In the materials testing, the forces acting on the material to be tested was measured using force transducer and a displacement of the point subjected force is measured using a displacement transducer [3], [8], [10]–[14]. There are two main problems in the dynamic force calibration method. Which are difficult to evaluate the imprecision in measurement of varied force. Then, there is the difficulty to evaluate the inaccuracy in time when the force being measured [6].

This problem can be overcome by using an optical interferometer-based Levitation Mass Method (LMM) [1], [5], [9], [15]. In the LMM, the inertial force of a mass levitated using pneumatic linear air bearing is used as the reference force applied to the objects under test [16]. In this case, force is defined as product of mass and acceleration. The acceleration must be accurately measured, so it is measured using optical interferometer. The optical interferometer could not be measure acceleration, but generated from velocity which obtains using principle of Doppler Shifting Frequency [1], [17]–[19].

At this LMM-based measurement, estimation of single frequency sinusoid with high resolution and high sampling rate is necessary to calculate Doppler Frequency Shift from interferometer's output [18], [20], [21]. To obtain the frequency, we need to calculate the output signal from photodiode which connected to digitizer by frequency estimation method program [22]. In this research, the new method which can improve the accuracy has been developed. The program is designed to be able to estimate the frequency of LMM data in the form of digitized waveform, then, digitized waveform is divided by the certain number of zero crossing before estimating the frequency.

2. Experiment

Figure 1 is the experiment set up of Levitation Mass method. In this method, inertial force of moving mass is used to calculate the dynamic force. The force used as a reference force is applied to the force transducer or material to be tested. In this case, the force is defined as the multiplication product of mass and acceleration.

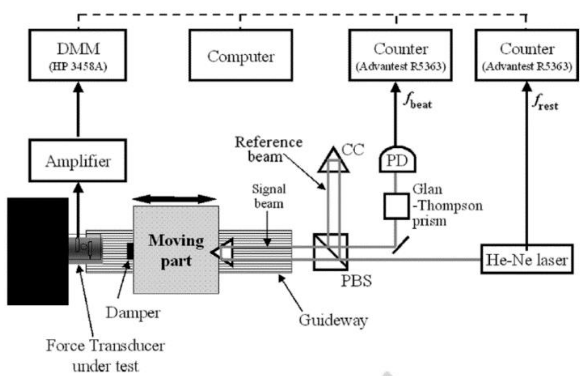

Figure 1. Experimental set up of Levitation Mass Method

The movement of the moving mass is made to move linearly with little friction. Linear movement with little friction is realized by using aerostatic linear air bearing. Then the acceleration need to be determined. Acceleration must be measured accurately by using optical interferometer. Optical interferometer can't measure acceleration directly, but it is obtained from velocity of moving mass obtained using the principle of Doppler shifting frequency.

A. Algorithm of Developed Program

Data output from the interferometer is a 16-bit binary data. Then developed program is designed to read and process the data by type of 16-bit binary data. The binary data processed into decimal data is then plotted against time obtained from its sample rate. This plot will generate data in the form of digitized waveform. Frequency of data required in the calculations and data processing LMM is the estimated frequency of the digitized waveform data. However, we cannot get this frequency directly, because, digitized waveform data of LMM is a single sinusoid with variable frequency. So we need a special treatment to be able to get an accurate frequency data. Then, the obtained digitized waveform data is filtered, this is done to reduce the error generated due to the offset of the system. Filtering to remove the offset is done by subtracting the data by average of all the data.

Frequency obtained by determining the zero crossing point and zero crossing time. Zero crossing detection is done by linear interpolation approach of 2 points around the x axis in which the value of the signal changes from negative to positive. Distance of two adjacent zero crossing is equal to one period of the wave, so that by knowing the zero crossing point and zero crossing time, then the frequency can be determined. In Figure 2. The red dot on the chart is a zero crossing point, N (1,2,3, etc.) showed zero crossing to (1,2,3, etc.), and t (1,2,3,etc.) is the zero crossing time for each zero crossing. At this zero crossing method, frequency can be calculated using the zero crossing time data obtained, the frequency can be calculated by the following equation.

$$f_1 = {}^{1}/_{(t_2 - t_1)} \tag{1}$$

$$f_2 = {}^{1}/_{(t_3 - t_2)} \tag{2}$$

$$f_3 = {}^{1}/_{(t_4 - t_3)} \text{...etc.} \tag{3}$$

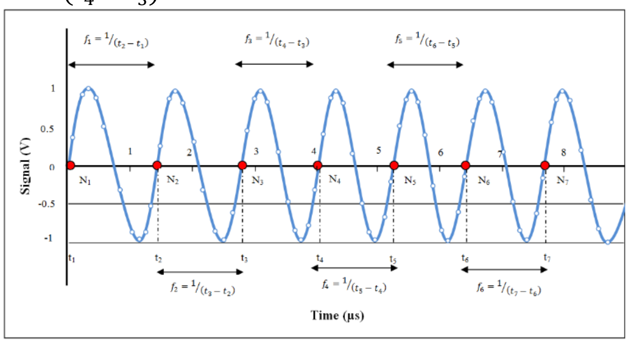

Figure 2. Algorithm of zero crossing method frequency estimation

In the estimation of the frequency with zero crossing method, only the first and last zero crossing information (in a certain interval) used in the calculation of the frequency, for example, can be seen in Figure 3. Frequency $f_1$and f_2 calculated by the following equation :

$$f_1 = {}^{4-1}/_{t_4 - t_1} \tag{4}$$

$$f_2 = {}^{7-4}/_{t_7 - t_4}, \text{ etc..} \tag{5}$$

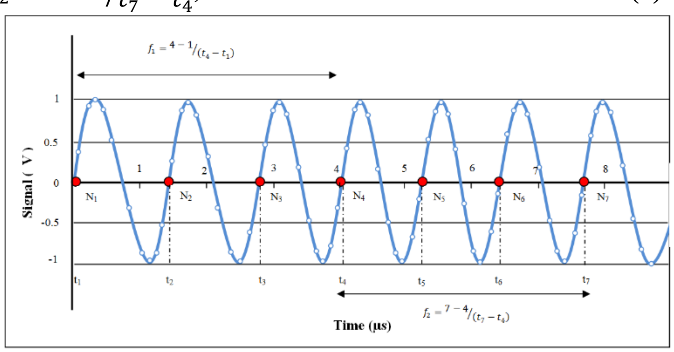

Figure 3. Algorithm of zero crossing frequency estimation for a particular range period (for example 3 wave period)

On this calculation, only information about the first and the last zero crossing (within certain ranges) used in the calculation (N_1 and N_4; $N_4$and N_7) with zero crossing time ($t_1$and t_4; t_4 and t_7), regardless of the zero crossing information between the two zero crossing point that used to calculate the frequency.

In the measurement, the presence of noise that affects the error cannot be avoided. In the program developed, carried out an optimization effort to reduce noise, resulting in more accurate estimates of frequency and will have an impact on LMM measurement accuracy. The principle used is almost the same as the method of averaging to eliminate noise. In the method developed, digitized waveform that has been filtered and determined its zero crossing is broken down and grouped by a specified number of zero crossing. At first glance, the algorithm used is almost the same as the algorithm used in Figure 3, however, contrast to the zero crossing method that only use first and last zero crossing, in the method developed, all information of the zero crossing point and zero crossing time is used in the calculation, so that the error can be minimized.

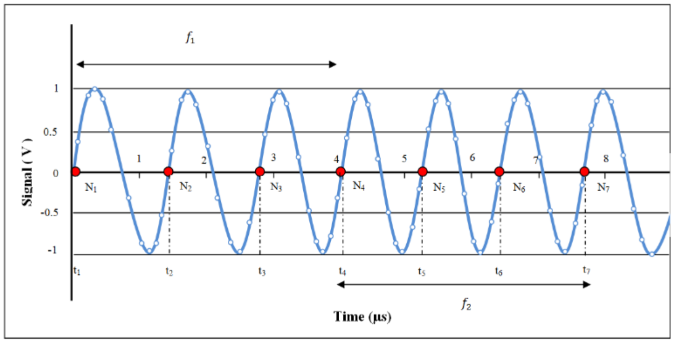

Figure 4. Algorithm of developed program (for example N=4)

In this study, the data processing is done by varying the number of zero crossing to determine the effect of segmentation or the number zero crossing (N) to the accuracy of data processing by the program. Frequency is determined by using the following equation:

$$f_j = \frac{N^3 - N}{12\sum_{i=0}^{N-1} i t_{i+j(N-1)} - 6(N-1)\sum_{i=0}^{N-1} t_{i+j(N-1)}} \quad (6)$$

Where:

f_j : Frequency (j= 1,2,3, etc)

N : Amount of zero crossing

t_i : Zero crossing time (i= 1,2,3, etc)

To be able to know the error generated in data processing by the developed program, then, a sinusoidal data waveform generated with the parameters that have been determined. Then the data is processed using the developed program. Error is obtained by comparing the parameters obtained from the estimation of the program with the actual parameters of the data processed. Then, to determine resistance of program developed to noise contained in the data, then the noise (Gaussian white noise) is added to previous signals that are generated with the same test as before.

B. Frequency Estimation and LMM Data Processing with Developed Program

There are some steps being taken in order to estimate these frequencies and process the LMM data using developed program.

1) Reading the binary data of dfbeat and dfrest

The first stage in estimation frequency of Levitation Mass method data is the manufacture of binary data readout program of dfbeat and dfrest then these data are plotted versus time obtained from the sampling rate, resulting in waveform

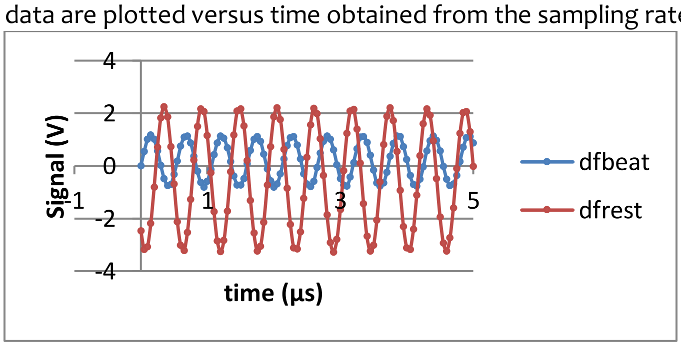

Figure 5. Waveform of dfbeat and dfrest

2) Filter the DC component of the signal

Data of fbeat and dfrest read by counter are AC and DC data component. For zero crossing calculation, only AC data that is used. So, the DC data should be filtered. DC data filtered by subtracting each data with the average of data.

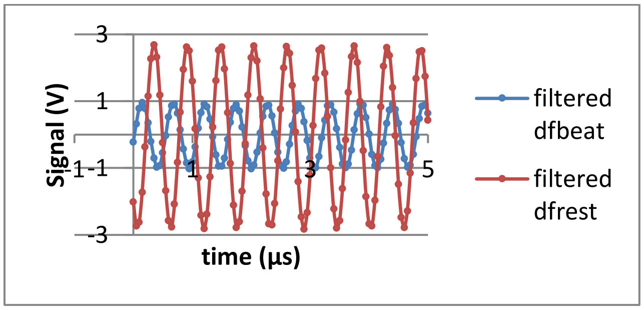

Figure 6. Filtered waveform of dfbeat and dfrest

3) The zero crossing detection and calculation of zero crossing time

The next step is zero crossing detection. Zero crossing detection is done by linear interpolation of the wave form signals that have been filtered.

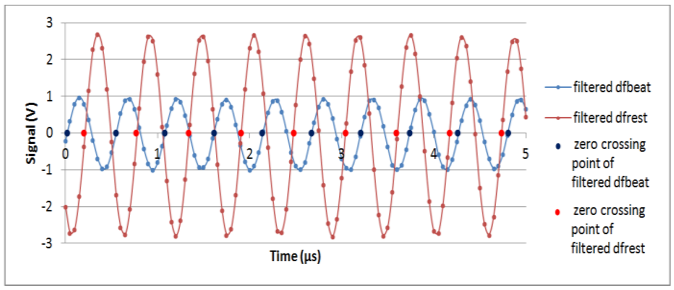

Figure 7. Zero crossing of filtered dfbeat and dfrest waveform

4) Frequency calculation

Frequency is calculated using the equation (6).

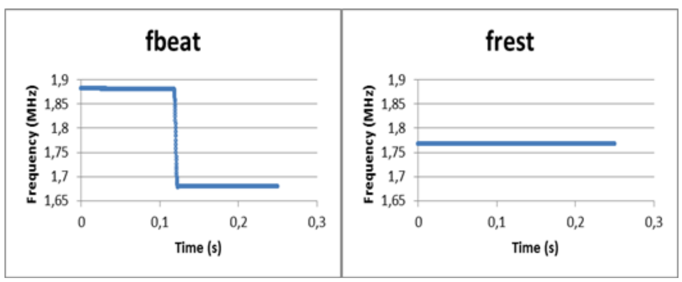

Figure 8. Beat and rest frequency estimation

5) Creating frest frequency interpolation program to fbeat time

To be able to perform calculations using the principle of Doppler Shift Frequency. fbeat and frest timing parameters must be same, whereas we have data fbeat with fbeat time and frest with frest time. So the value we have to interpolate frest data to fbeat's time.

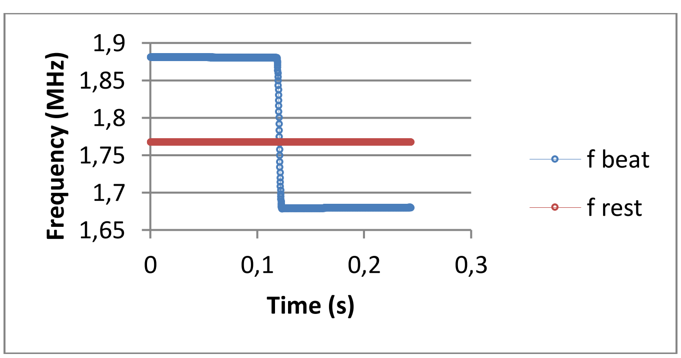

Figure 9. Frequency vs time after interpolated

From the frequency data, we can get information about the velocity using the Doppler Frequency Shift principle. Once, we get information about the velocity, so we can get any information about acceleration, position and force.

$$v = \frac{\lambda}{2}(f_{Doppler}) \quad (7)$$

$$f_{Doppler} = -(f_{beat} - f_{rest}) \quad (8)$$

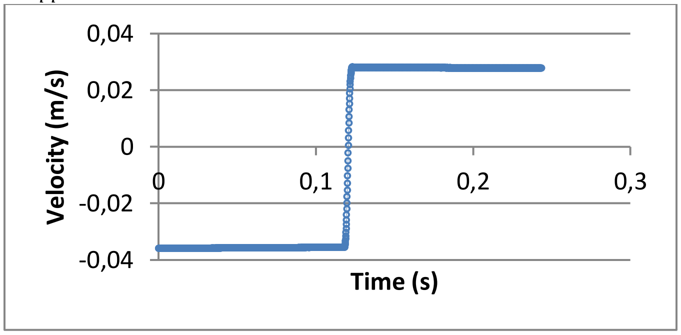

Figure 10. Velocity vs time

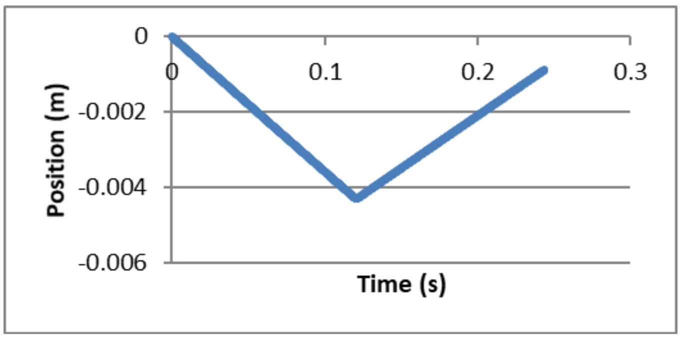

Figure 11. Position vs time

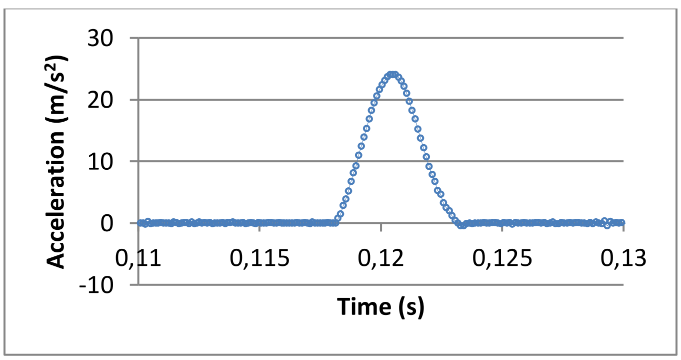

Figure 12. Acceleration vs time

C. Calculation of zero force, zero time and zero position

Calculation of zero force, zero time and zero position is done in order to clearly analyze the mechanical parameters of the measurements, during and after the collision. In the previous program, the chart only shows the mechanical parameters and the results of the inertial measurement data recording until the end of data recording, so, information regarding the time of collision, position and force cannot be analyze accurately. Zero force is a condition when the impact force is equal to zero shortly when the moving part is starting to collide with the material under test. Zero position is the position of the moving part shortly when the moving part is starting to collide with material under test. Zero time is set to be zero when moving part is starting to collide with the material under test.

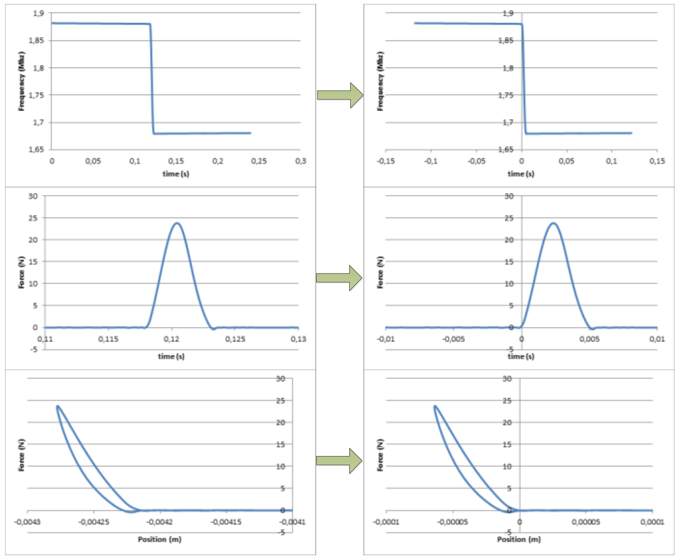

Figure 13. Graph of the data processing LMM before and after zero time and zero position calculation.

Figure 13. shows a graph of the LMM data processing result before and after the calculation of zero time and zero position. In the graph on the left, information about the collision between the moving parts and material under test cannot be obtained accurately. The time of collision, the duration of collision, and the shifting of material (due to the elasticity of material under test) can only be estimated without an accurate value. In the LMM data processing with zero time and zero position calculation, decreasing of frequency as the result of collision, duration of collision and the shifting of material (due to the elasticity of material under test) can be obtained accurately.

D. The development of LMM Data Processing Program based on Graphical User Interface (GUI)

Program created before is still a console-based program and consist of several separate programs with specific functions, so after each measurement is completed, code-based programs should be created to process the data. Changes in measurement parameter should be done from the program code, so only developer of the code can use the program. To overcome this, the program was developed based on Graphical User Interface (GUI) to facilitate the user to operate the program. This program can read and process Levitation Mass Method measurement data, so information about mechanical parameter will be obtained. Data processing results will be stored in a specified directory in the form of CSV files (compatible with Ms. Excel) so it is easy to be plotted.

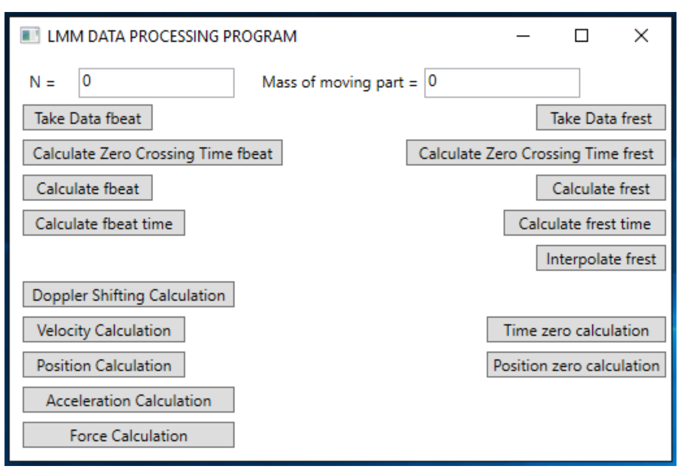

Figure 14. Layout of GUI-based LMM data processing program

GUI-based program is very easy to be used and operated. The previous program can read and process the data to estimate the frequency, but the frequency data should be processed using Ms Excel to get information about mechanical parameters like velocity, acceleration, force and distance to be analyzed. Using this GUI-based LMM processing program, the complex calculations using Ms Excel is no longer needed. The data will be processed directly by clicking button on the program window.

3. Testing and Evaluation of Method

Testing and evaluation is done by using a program that has been created to process data signals that are generated by a predetermined signal parameter. The testing signal is generated sine signal with the signal parameter that almost the same as data signal of Levitation Mass method. Then, to see resistance against the noise, sine signal generated is added with a certain level Gaussian noise and then processed by the program that has been created. The stages of data testing are carried out as follows.

1) Generate sine signal as testing data

Testing data used in the testing program is the data of sine signal. The signal is generated using C# programming language Visual Studio. The generated signal has the specific parameters with sample rate 20 MHz, the amount of data 5.000.000, frequency 2 MHz, and the amplitude 3.

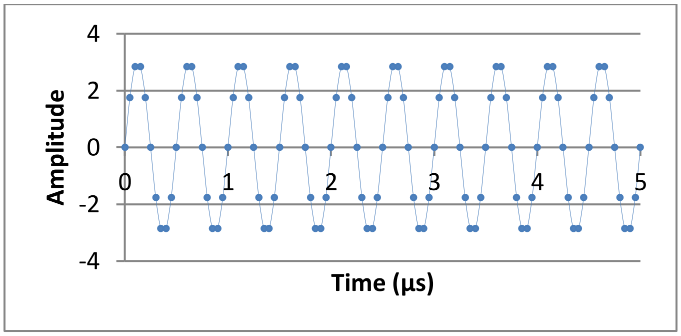

Figure 15. Sine data waveform as testing data

2) The addition of Gaussian noise in the sine data signal

After the sine data as in Figure 15 are generated, the data is added with certain level of Gaussian noise (10%). The addition of noise in the sine data is also created using C# programming language Visual Studio.

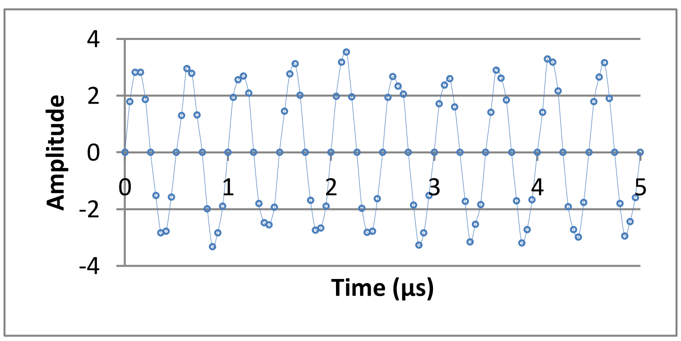

Figure 16. Sine data waveform with Gaussian noise

3) Process the testing data with the developed program

The next phase is using the developed program to process sine data in Figure 16. Error is obtained by comparing the difference between the data processing program (estimated frequency) with the real frequency of the processing signal, divided by the processing data signal. Testing is done by varying the segmentation of the data (N). The testing results of this program can be seen on the table 1.

Table 1. Error of data processing's result

N	*Error*(%)
N=50	$3{,}36\ x\ 10^{-9}$
N=100	$2{,}44\ x\ 10^{-9}$
N=200	$1{,}98\ x\ 10^{-10}$

There are several methods that have been developed in the LMM data processing, as can be seen in Table 2.

Table 2. Comparison of data processing's result of some methods [22]

Methods	Error (%)
Zero-cross averaging	$7{,}51\ x\ 10^{-3}$
ZAM	$2{,}31\ x\ 10^{-3}$
ZFM	$1{,}10\ x\ 10^{-3}$
Sine wave fitting	$7{,}96\ x\ 10^{-4}$
Zero-crossing sine wave fit	$8{,}69\ x\ 10^{-4}$
FFT	1,95
Developed method (N=50;N=100;N=200)	$3{,}36\ x\ 10^{-9}$; $2{,}44\ x\ 10^{-9}$; $1{,}98\ x\ 10^{-10}$

FFT conventional methods have the greatest error, making it less suitable for use in the estimation of the frequency for LMM data processing; ZAM and ZFM has error about $2{,}31\ x\ 10^{-3}$ and $2{,}31\ x\ 10^{-3}$. Method that we developed has a smallest error compare to other methods. So, our method is the best method use as LMM data processing program.

4) Testing the effect of data segmentation in LMM data processing

In the previous test using test data generated using the programming language C # in Visual Studio (table 1.), it can be seen that the greater the segmentation done, then the smaller the error. So, we need to test the program directly to LMM data to look the effect of data segmentation to noise resistance of developed program. The result of this testing can be seen in Fig 17, Fig 18, Fig 19 and Fig 20. From the figures, it can be seen that the greater data segmentation done, the smaller noise and error.

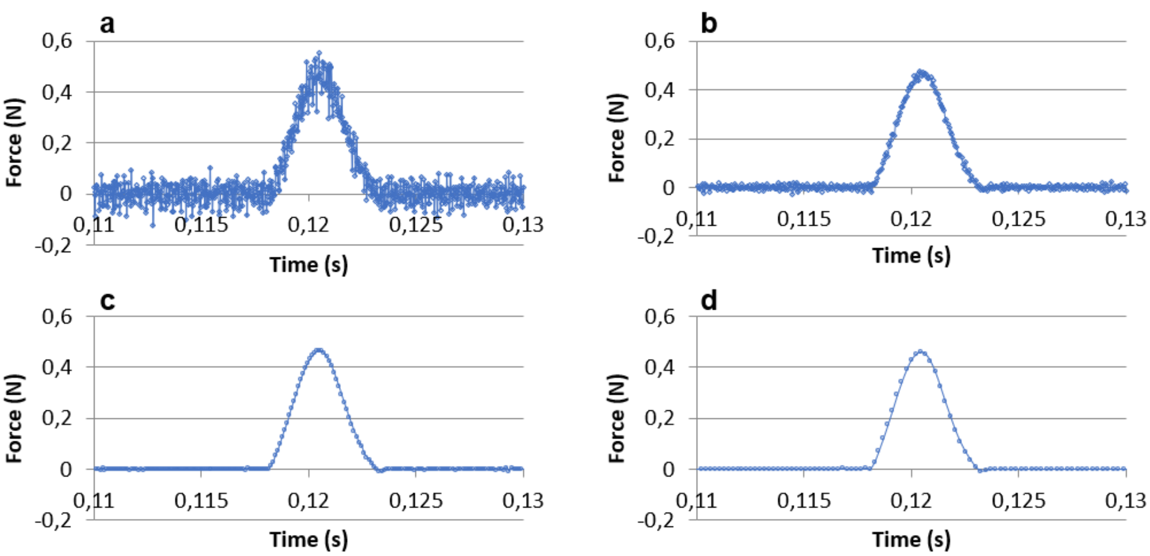

Figure 17. LMM data processing result with a. N = 50, b. N = 100, c. N = 200, d. N = 400

4. Summary

From the research that has been done can be concluded that the programs that have been developed is good to be used as LMM data processing program. Segmentation performed on these data proved to be able to improve the accuracy of frequency estimating and more resistance to noise. It can be seen that error is dependent to data segmentation. The developed program also proved to be better than the other methods. Conventional methods FFT is a program that generates the greatest error to estimate the frequency on this LMM data processing. So that the FFT is not suitable for frequency estimation on the LMM data processing, error generated is about 1.95%. The other methods are zero-cross averaging, ZAM, ZFM and others have a relatively small error, but still greater than the error generated by the program that we developed. So, it can be concluded that the program is the best program compare to other programs.

GUI-based program is easy to use. Data processing is done simply by pressing a button that contains special functions that have been programmed. LMM data processing can be done quickly because the program being developed is a program with multiple functions simultaneously. With the calculation of zero time and zero position, the information and measurement data can be analyzed accurately. Each button on the program already represents a function and calculations required in data processing so that the calculation LMM outside the program by using software such as MS Excel is not needed anymore. Data is stored in the form of programming results csv file and compatible with MS Excel so can be plotted directly.

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