Journal of Engineering Science and Technology
Special Issue on SU18, February (2019) 22 - 32

FREQUENCY CHARACTERISTICS OF SLOT-LESS AND SLOT TYPE LINEAR OSCILLATORY ACTUATOR FOR FOOD PROCESSING APPLICATION

FARINA SULAIMAN[1], RAJA NOR FIRDAUS[2,*],
SITI ZULAIKA, FAIRUL AZHAR[2], ARAVIND CHOCKALINGAM
VAITHILINGAM[3], NORHISAM MISRON[4]

[1]Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia
[2]Power Electronics and Drives Research Group, CeRIA, UTeM
[3]School of Engineering, Taylor's University, Selangor, Malaysia
[4]Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
*Corresponding Author: norfirdaus@utem.edu.my

Abstract

This paper discusses *RL* frequency characteristics of slot-less and slot-type linear oscillatory actuator for food processing application. The *RL* characteristics experiment is carried out to investigate the characteristics of resistance and inductance for various value of frequency. The main objective of this research is to study the relationship of frequency response toward *RL* characteristics. The reason for this investigation is due to the controllable DC rectifier that will provide DC in pulse width modulation (PWM) signal to obtain the variable value of DC in average. The value of resistance and inductance is different when the shaft moves at a certain position. Physically, the slot-type linear motor was mounted on the linear jig and the shaft has been fully pulled out. The value of the resistance and inductance was measured by using a LCR meter. In conclusion, this paper provides an overview of *RL* characteristics of slot-less and slot-type linear motor.

Keywords: Linear oscillatory actuator, *RL* characteristics.

1. Introduction

A linear oscillatory actuator (LOA) includes a magnetic pole forming portion that includes an electromagnet and base, magnetic blocks each of which includes a permanent magnet attracted or repelled by the electromagnet to reciprocate, elastic suspensions for supporting the magnetic blocks, and at least one coupling spring portion that couples the magnetic blocks. LOA is widely used in linear motor shavers, electric toothbrushes, and mobile phone vibrators as high-speed oscillatory driving devices. LOA outputs short-stroke reciprocating movement directly without any other auxiliary motion transformation components and has the advantages of high efficiency, low abrasion and long lifespan [1-3]. Thus, it has attracted accumulating focus recently and has been applied to linear compressors, linear pumps and other industrial applications [4-6]. The maximum amplitude of the motor is obtained at a resonant frequency that is determined by the spring constant and the mass of the motor. One of the characteristics of LOA is the frequency control. Suzuki et al. [7] studied about active vibration control of drum type of washing machine using a linear oscillatory actuator. The author proposes an evaluation method of vibration reduction for a linear oscillatory actuator using a fundamental frequency force. The proposed method is evaluated by comparing fundamental frequency forces with and without active control. Sakai et al. [8] studied the prediction and prevention of losing steps in a helical teethed linear actuator. This author describes the prediction and prevention of losing steps in the helical teethed linear actuator (HTLA) for artificial muscle. When the rapid external force is applied to the HTLA, it becomes a state of losing steps. Therefore, it is important to predict and prevent this phenomenon. Another author has proposed the semi-analytical calculation of a propulsion force, generated between a moving permanent magnet and a rectangular air-core coil.

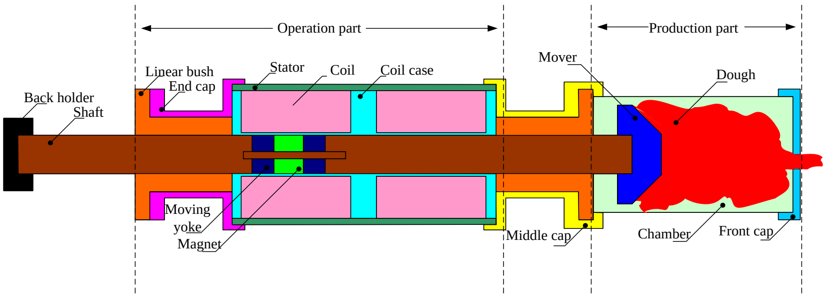
The proposed solution is for the design and analysis of a linear actuator for contactless positioning systems [9]. The linear oscillating actuator is a kind of electromagnetic device, providing high frequency short-stroke reciprocating motion directly without extra motion transfer mechanisms. It shows satisfactory efficiency and power density especially with high frequency and large load [9]. Wang et al. [10] studied about design, analysis and experiments of novel short-stroke linear loading system based on the axial-magnetized voice-coil motor for linear oscillating actuator. The proposed method is used to achieve a fast response, low inertia and stable loading force, the symmetrical axial magnetized array is adopted among the various magnetic configuration solutions. Moreover, the non-ferromagnetic and non-conductive mover is designed for both low inertia and eddy current suppression [10]. Fezzani [11] had made a comparison between Matlab and position sensor for finite element analysis of a linear actuator used by biomedical application. Low energy consumption, electrical sensitivity, inerrability, and precision are some of the advantages of the linear actuator to the biomedical industry. Those criteria allow the creation of new medical devices to monitor the biological parameters of the human body as well as devices designed to increase the the effectiveness of treatments, reduce discomfort and improve health and well-being [12].

This paper discusses frequency characteristics of slot-less and slot type LOA for food processing application. Two type of linear motor which is slot-less and slot-type is investigated in terms of *RL* characteristics and value of impedance and phase difference over frequency response. The reasons for this investigation are due to the controllable DC rectifier that will provide DC in pulse width modulation (PWM) signal to obtain the variable value of DC in average. Basically, the DC supply need to be controlled since it could help in controlling the current and thus controlling the thrust.

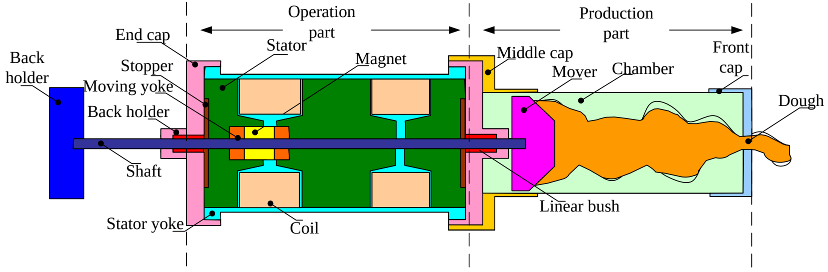
2. Basic Structure of LOA for Food Automation Application

Figure 1(a) shows the cross-sectional model of the slot-less linear motor for tart moulding device, which consists of the stationary part and moving part. The stationary part includes a stator yoke and coil. When the back holder is pressed, the shaft will move forward and the dough will be produced through production part. Inside the stator, there are moving yokes and magnet, which point to be moving part. The moving yoke is used to channel all the flux to the coil so that the flux will be distributed to the desired parts without any losses. The production and operation part is placed separately. The operation part, which is inside the stator yoke consists of a magnet, moving yokes, coil, coil case and shaft. While the production part or inside the chamber consists of mover and dough.

Figure 1(b) shows the cross-sectional model of the slot-type linear motor for tart moulding device, which consists of the stationary part and moving part. The operation of slot-type is similar to slot-less where the dough will be produce as the back holder is pressed forward. The stationary part includes a stator yoke and coil. Meanwhile, the moving part includes moving yokes and a permanent magnet.



(a) The slot-less linear motor for tart moulding device.

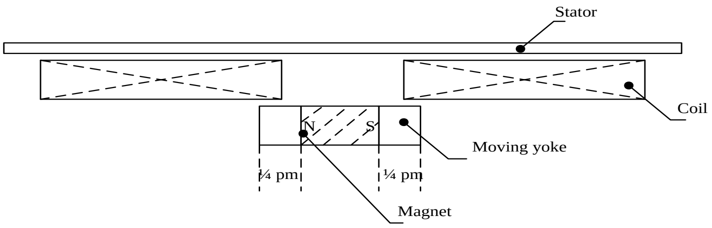


(b) The slot-type linear motor for tart moulding device.

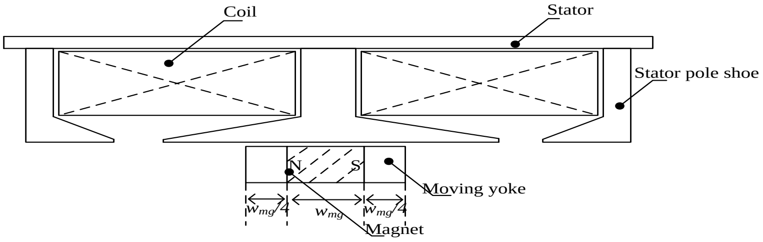
Fig. 1. Slot-less and slot-type linear motor for tart moulding device.

The moving yokes must be designed at a quarter of the size of the permanent magnet as shown in Fig. 2(b). The production and operation parts are placed separately. The operation part, which is inside the stator yoke, consists of slot-type steel, magnet, coil, and shaft. While the production part or inside the chamber consists of mover and dough.

Figure 2 shows only the basic structure at the operation part. Figure 2(a) is the basic structure of the slot-less linear motor, while Fig. 2(b) is the basic structure for the slot-type linear motor. The main structure for slot-less motor consists of a coil, stator, magnet, and moving yoke. The main structure for slot-type motor consists of coil, stator, magnet, moving yoke and slot-type steel. In this project, there are two coils will be used to interact with the magnet when the dc supply is turned ON.



(a) The basic structure of a slot-less linear motor.



(b) The basic structure of a slot-type linear motor.

Fig. 2. The basic structure of slot-less and slot-type linear motor.

A linear oscillatory actuator (LOA) includes a magnetic pole forming portion that includes an electromagnet and base, magnetic blocks each of which includes a permanent magnet attracted or repelled by the electromagnet to reciprocate, elastic suspensions for supporting the magnetic blocks, and at least one coupling spring portion that couples the magnetic blocks. LOA is widely used in linear motor shavers, electric toothbrushes, and mobile phone vibrators as high-speed oscillatory driving devices.

3. Theory of Frequency Characteristics in LOA

In LOA, main frequency characteristics of the motor are contributed by resistance and inductance. Both resistance and inductance are impedance. Impedance is used to measure the opposition of a circuit which presents current when a voltage is applied. Quantitatively, the impedance of a two-terminal circuit element is the ratio of complex representation of a sinusoidal voltage between its terminals to the complex representation of current flowing through it. In general, it depends upon the frequency of the sinusoidal voltage. Impedance is a complex number, with the same units as resistance, for which the SI unit is ohm (Ω). Its symbol is usually Z, and it may be represented by writing its magnitude and phase in the form $|Z|\angle\theta$. All the data recorded from the experiment is used to find the value of impedance [Z], theta [θ] and omega [ω]. The formula to calculate the required values are as follows as equation (1), where Z is the impedance of the coil in [Ω], R is the resistance of the coil in [Ω] and $j\omega L$ is the inductance of the coil in (Ω).

$$Z = R + j\omega L \tag{1}$$

A resistance-inductance circuit (*RL*) is an electric circuit consist of resistor and inductor driven by voltage or current source. The complex impedance Z_L with inductance L is shown in equation (2) where Z_L is measured in ohm while L is measure in H. Equation (3) shows relationship of frequency in complex number where j represents an imaginary unit, j^2=-1, α is the exponential decay constant (in radians per second), and w is the angular frequency in radian per second.

$$Z_L = L_s \quad (2)$$

$$s = \alpha + jw \tag{3}$$

Frequency characteristics of LOA are also known as *RL* characteristics. Basically, the purpose of *RL* characteristics is to investigate the characteristics of resistance, R and inductance L in the fabricated LOA. The R and L characteristics show the effect of frequency of supply to the resistance and inductance parameter of LOA. The reasons for this investigation are due to the controllable DC rectifier that will provide DC in pulse width modulation (PWM) signal to obtain the variable value of DC in average. Basically, the DC supply need to be controlled since it could help in controlling the current and thus controlling the thrust. An *RL* characteristic was observed at a range of frequency between 10 Hz to 100k Hz. This range of frequency represents the operation of less motor. While measuring the frequency characteristics, the slot-less linear motor mover was moved at its full range of displacement so that the *RL* characteristics of the linear motor at the full range of mover displacement can be captured. Furthermore, the frequency characteristics were measured for both slot-less and slot-type linear motor which will be shown in the next session. The fabricated LOA contains 2 coils, which are at the left and right. Each coil inside the LOA has 995 turns by using a 0.7 mm diameter of the copper wire. Fundamentally, the frequency characteristics include the value of phase difference, inductance L, resistance R and impedance Z for a range of frequency 12 Hz until 100 kHz. The value of and Z had been calculated by using equation (1), (4) and (5).

$$\theta = \tan^{-1} \frac{\omega L}{R} \tag{4}$$

where θ is the degree between impedance and resistance in [rad], ωL is the inductance of the coil in [Ω] and R is the inductance of the coil in [Ω] and f is the frequency of the linear motor in [Hz].

$$\omega \equiv 2\pi f \tag{5}$$

There are also force involved a linear motor. Basically, force is generated when the shaft moves forward toward production part. The relationship between force and inductance are shown in equation (6) where I is the coil current while x is displacement in meters.

$$F \equiv (I^2/2)(\frac{dL}{dx}) \tag{6}$$

4. Theory of Frequency Characteristics in LOA

Figure 3 shows the overall process of *RL* characteristics experiment is conducted. This experiment is set to have the movement of the shaft or mover from position 0 mm to 100 mm for slot-less and 110 mm for slot-type by using one size diameter of the coil, which is 0.7 mm. For every 10 mm movement of the shaft, the result of the inductance and resistance was taken.

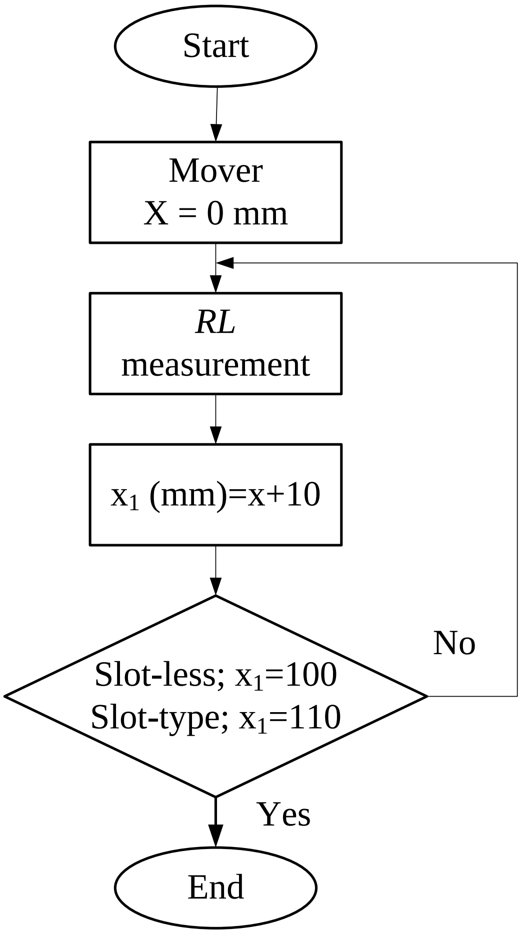


Fig. 3. Overall process of *RL* characteristics experiment.

Figure 4 shows a diagram for *RL* experiment. This experiment is conducted to measure the *RL* characteristics of this fabricated linear motor. The linear motor is placed on the jig and on hold by the holder that has been specially designed. The two connector of the LCR meter is then connected with the positive (+) and negative (-) polarity wire of the fabricated linear motor. At the jig, there is an indicator at the bottom of the moving jig. The indicator is used to measure the movement of the shaft for every 10 mm. The mover is set at 0 mm as its starting position. The data needed is recorded for every 10 mm movement of the mover.

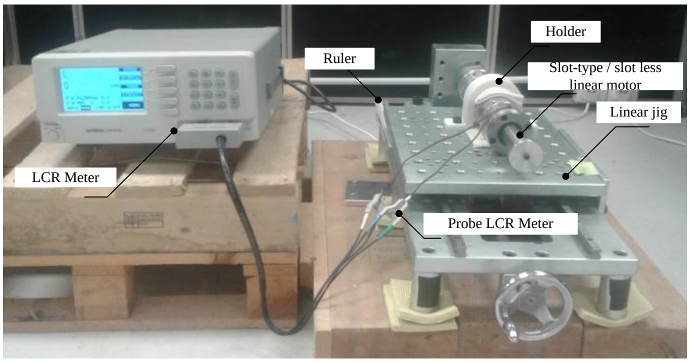
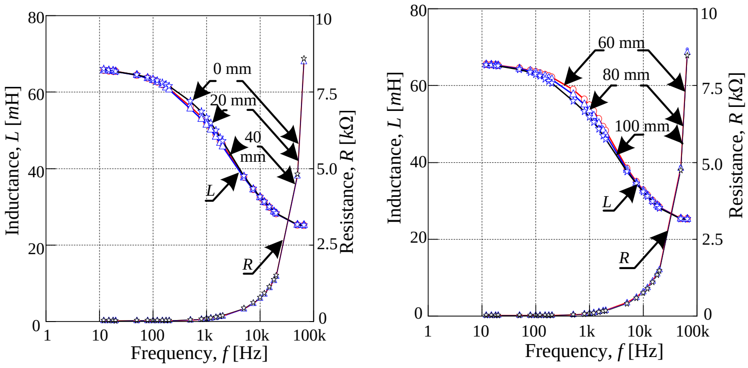


Fig. 4. Measurement setup.

5. Frequency Characteristics of Slot-Less

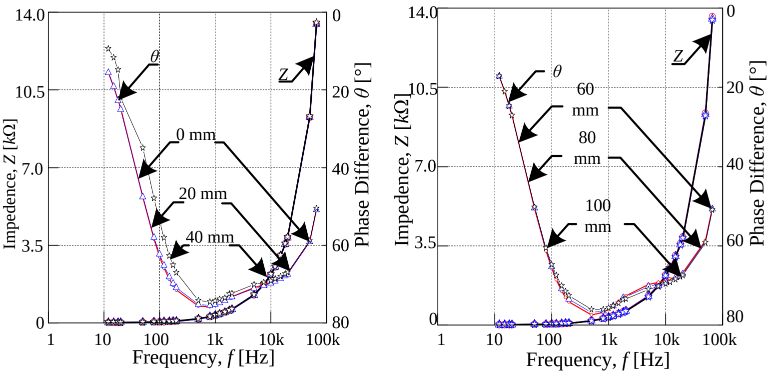
Figure 5 shows *RL* characteristics of the slot-less linear motor. Figure 5(a) is the result of *RL* characteristics at position 0 mm, 20 mm and 40 mm while Fig. 5(b) is the result at position 60 mm, 80 mm and 100 mm. The maximum resistance is 8.48 kΩ at a frequency near to 100 kHz while minimum resistance is 30 Ω at a frequency near to 10 Hz. For inductance, the maximum value of inductance is 66 mH at a frequency near to 10 Hz while minimum inductance is 25 mH at a frequency near to 100 kHz. There are only very small changes in value for resistance and inductance at each position. For position 60 mm, 80 mm and 100 mm, the result is similar to position 0 mm, 20 mm and 40 mm for maximum and a minimum value of resistance and inductance. From Fig. 5(b), it can be seen that the value of inductance changes at a frequency range from 1 kHz to 10 kHz. Position at 60 mm has a higher inductance compare to position 80 mm and 100 mm where the percentage different at this range is 5 %. It shows that as frequency increased, resistance for each position will increase. This is opposite condition for inductance where inductance decrease as frequency increased. The most suitable frequency to be used is below 100 Hz. This is because the value of resistance and inductance is stable and low at this range of frequency. If higher frequency used in this research, it will change the value of resistance and inductance and cause the performance of LOA changes. It also can be seen in the industry, mostly motor operate at a frequency below 100 Hz.



(a) Position 0 mm to 40 mm **(b) Position 60 mm to 100 mm**

Fig. 5. *RL* characteristics of the slot-less linear motor.

Figure 6 shows the effect of frequency to the impedance and phase difference for the slot-less linear motor. Figure 6(a) is the result at position 0 mm, 20 mm and 40 mm. Maximum phase different is position 40 mm which is 75° at the frequency of 500 Hz while the minimum phase difference is 93° at the frequency of 12 Hz. The value of θ is same at every position but there is slightly difference for at position 40 mm. This is due to the increasing value of resistance, R with the increasing of displacement. For impedance, the maximum impedance is 13.45 kΩ at a frequency near to 100 kHz while minimum impedance is 30 kΩ at a frequency of 12 Hz. Figure 6(b) shows result at position 60 mm, 80 mm and 100 mm. All of the value of impedance is same at all displacement. This shows that the value of impedance had been saturated.



(a) Position 0 mm t0 40 mm **(b) Position 60 mm to 100 mm**

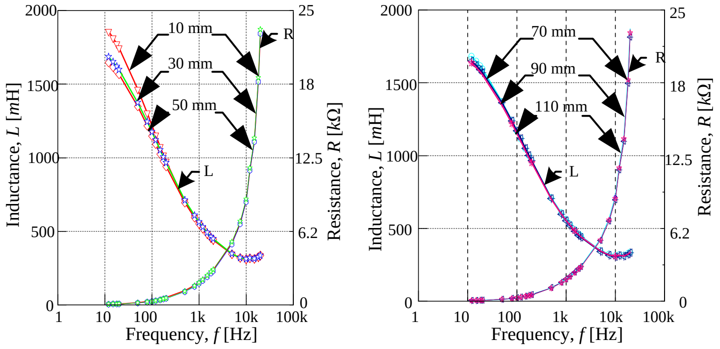
Fig. 6. Effect of frequency to the value of impedance, Z and phase difference, θ for slot-less linear motor

The maximum value of impedance is 13.46 kΩ at a frequency near to 100 kHz while the minimum value of impedance is 16 kΩ at a frequency of 12 Hz. For phase difference, the maximum value of θ is 77° at the frequency of 500 Hz while the minimum value of θ is 17° at the frequency of 12 Hz. From Fig. 6, it can be seen that as impedance increase towards frequency, the phase difference will be increased.

6. Frequency Characteristics of Slot-Type

Figure 7 shows RL characteristics of the slot-type linear motor. Figure 7(a) is the result for RL characteristics at position 10 mm, 30 mm and 50 mm while Fig. 7(b) results at position 70 mm, 90 mm and 110 mm. For Fig. 7(a) maximum inductance is 1850 mH for frequency 12 Hz while minimum inductance is 301 mH for a frequency near to 100 kHz. From the figure, it is shown that inductance is higher at position 10 mm while maintained at position 30 mm to 50 mm. For resistance, maximum resistance is 23.2 kΩ for a frequency near to 100 kHz while minimum resistance is 6.3 kΩ for frequency 12 Hz. Result for frequency is similar for position 10 mm to 50 mm. For Fig. 7(b), the result for inductance and resistance is maintained at position 70 mm, 90 mm and 20 mm. The maximum inductance is 1600 mH for frequency 12 Hz while minimum inductance is 330 mH for a frequency near to 100 kHz. For resistance, maximum resistance is 22.6 kΩ for a frequency near to 100 kHz while minimum resistance is 0.6 kΩ for frequency of

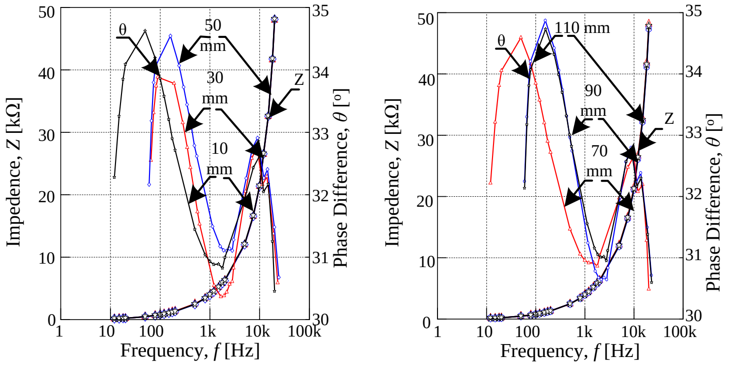
12 Hz. It shows that as frequency increased, resistance for each position will increase. This is opposite condition for inductance where inductance decrease as frequency increased.



(a) Position 0 mm to 50 mm (b) Position 70 mm to 110 mm

Fig. 7. *RL* characteristics of the slot-type linear motor.

Figure 8 shows the effect of frequency to the value of impedance and phase difference for the slot-less linear motor. Figure 8(a) is the result at position 10 mm, 30 mm and 50 mm. Maximum phase different is 34.8° for frequency 80 Hz at position 10 mm while minimum phase difference is 30.4° for frequency 2 kHz at position 30 mm. From Fig. 8(a), it can be seen that at all position, phase displacement is different but impedance for all position is the same.



(a) Position 0 mm to 40 mm (b) Position 60 mm to 100 mm

Fig. 8. Effect of frequency to the value of impedance, Z and phase difference, θ for slot-type linear motor.

The maximum value of impedance is 48.3 kΩ while the minimum value of impedance is 0.8 kΩ. Figure 8(b) shows the result of frequency over phase different and impedance at position 70 mm, 90 mm and 110 mm. Maximum phase different is 34.8° at position 70 mm with frequency 200 Hz, while the minimum phase difference is 30.85° at position 70 mm. For impedance, the maximum value of impedance is 49.1 kΩ at all position. The minimum value of impedance is 0.7

kΩ at frequency of 12 Hz. In this research, it can be seen that the most suitable frequency used is suggested to be below than 100 Hz because the value of resistance and inductance is stable and low at this range of frequency. If a higher frequency is used it will change the value of resistance and inductance which will affect the performance of the LOA.

7. Conclusion

In this paper, *RL* frequency characteristics of slot-less and slot-type linear oscillatory actuator for food processing application is investigated. The experiment is carried out to investigate the characteristics of resistance and inductance for various value of frequency. The value of resistance and inductance is different when the shaft moves at a certain position. In this research, it can be seen that the most suitable frequency to be used is suggested below than 100 Hz because the value of resistance and inductance is stable and low at this range of frequency. If a higher frequency is used it will change the value of resistance and inductance which will affect the performance of the LOA.

Acknowledgements

The author would like to thank Skim Zamalah UTeM and Universiti Teknikal Malaysia Melaka (UTeM) for providing the research grant GLuar/PPRN/2017/FKE-CERIA/G00050 and PJP/2017/FKE/HI12/S01537.

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