Characteristics of the Attractive Force And The Thrust Force of Linear Induction Motor driven by Modified Trapezoidal Modulated Power Source

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ABSTRACT: We have proposed Linear Induction Motor(LIM) is driven by the power source combining the fundamental component and some high frequency components. It is easy to control of the thrust and attractive force by changing the ratio of each frequency component. In this paper, we propose the usage of the modified trapezoidal modulated power source. The modified trapezoidal waveform has the fundamental component and some harmonics components. The fundamental component is larger than that of the sinusoidal waveform in the equal maximum amplitude. The ratio of harmonics components is controlled easily. Therefore, the modified trapezoidal power source has smaller capacity than the conventional sinusoidal power source. We verify the characteristics of the attractive force and the thrust force by experiment.

1 INTRODUCTION

Linear Induction Motor(LIM) has the unique merits, direct drive, contact-less suspension, no emission of dusts and so on. The LIM is applied to the maglev transport system as the traction component. The usual maglev transport systems are combined the levitation system with the traction system. It has the complicated structure.[1]-[3] We have proposed the novel transportation system without the levitation magnets.[4] In this system, the thrust force and the attractive force of the LIM are used. And they have to be controlled simultaneously. Therefore we have proposed the new control method of the forces to use the power source having two different frequency components, one has the low frequency and the other has the high frequency. The low frequency component is mainly used to control the forces for the suspension and the traction of the bogie. The high frequency component is used to adjust the forces.[7], [8]

In this paper, we propose the usage of the modified trapezoidal modulated power source to drive the LIM. The modified trapezoidal waveform is added the rectangular wave on the trapezoidal wave. The output of the modified trapezoidal modulated power source has the fundamental component and the harmonics components. In addition, the ratio of the fundamental component and some high harmonics component is changeable by the addition ratio of the trapezoidal wave. It is one of the power sources having some different frequency components. Additionally, it has the high utilization of the power source and the reduction of the switching losses in the inverter. We verified the characteristics of the attractive force and the thrust force of the LIM driven by the modified trapezoidal modulated power source.

2 PROPOSED MAGLEV SYSTEM

2.1 Structure of systems

Figure.1 shows the usual maglev system and the proposed one. In the usual system, the traction and the levitation system are implemented separately. The LIM is used for the traction system and the levitation magnets are used for the levitation. Therefore the attractive force of LIM is controlled in order not to affect the levitation system. The proposed maglev system has only the LIM without the levitation magnets as shown Figure.1 (b). The attractive force of LIM is used for the levitation system. In the proposed system, the LIM has the united function of the traction and the levitation. The proposed system has compact structure, low cost, easy maintenance.

2.2 *The attractive force and thrust force controlled by power source including high frequency component.*

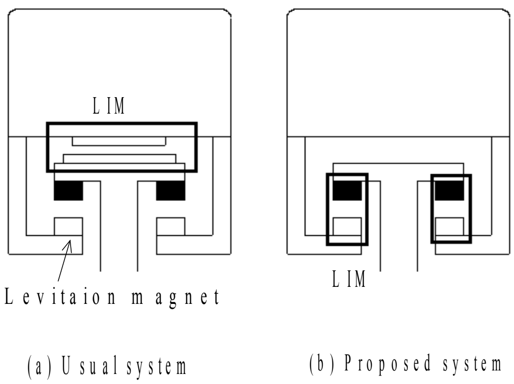


Figure.1 Usual maglev system and proposed maglev system

In the proposed maglev system, it is necessary to control the attractive force and the thrust force of the LIM simultaneously. We have proposed the control method to use the power source having the two different frequency components, one has the low frequency and the other has the high frequency. In this operation, the attractive force and thrust force is summed of the force of the low frequency component and the high frequency component. It is easy to control.

Theoretically the thrust force and the attractive force depend on slip frequency and the flux density. And the forces are proportional to square of flux density. Therefore, these forces are calculated by the Equation 1.

$$F = g(f_s)\,B^2 \qquad (1)$$

where, $g(f_s)$ = force coefficient which is function of slip frequency.

When the LIM is driven by the power source including the high frequency component, the low frequency component of flux density (B_L) and high frequency component of flux density (B_H) are described as Equation 2.

$$\begin{aligned} B_L &= B_l \sin(2\pi f_{sl} t) \\ B_H &= B_h \sin(2\pi f_{sh} t + \varphi_h) \end{aligned} \qquad (2)$$

where, B_l = Amplitude of B_L, B_h = Amplitude of B_H. f_{sl} = slip frequency of the low frequency component. f_{sh} = slip frequency of the high frequency component, φ_h = phase delay against the low frequency component.

The time average of the total force (F_{ave}) is calculated as Equation 3.

$$\begin{aligned} F_{ave} &= f_{sl}\int_0^{\frac{1}{f_{sl}}} g(f_{sl}, f_{sh})\,(B_l^2 + B_h^2)dt \\ &= f_{sl}\int_0^{\frac{1}{f_{sl}}} g(f_{sl}, f_{sh})\,(B_l^2 + 2B_lB_h + B_h^2)dt \\ &= g(f_{sl},0)\frac{B_l^2}{2} + g(0,f_{sh})\frac{B_h^2}{2} \\ &= F_{low,ave} + F_{high,ave} \qquad \because \int_0^{\frac{1}{f_{sl}}} 2B_lB_h dt = 0 \end{aligned} \qquad (3)$$

where, $F_{low,ave}$ and $F_{high,ave}$ are the time average force of the low frequency component and high frequency component respectively.

According to the Equation 3, the total force is sum of the forces generated by the different frequency component of the flux density. The flux density is controlled by the input current. The flux density has the same frequency of the input current. Therefore, when the power source provides the input current including some different frequency components sufficiently, it is easy to control the forces.

3 MODIFIED TRAPEZOIDAL MODULATED POWER SOURCE

We propose to use the three phase modified trapezoidal modulated inverter to drive LIM. The modified trapezoidal signal has the fundamental component and the harmonics. The modified trapezoidal modulated inverter is used to reduce the torque ripple of the PM motor having the non-sinusoidal electromotive voltage by the harmonics.[9]

Figure.2 shows the modified trapezoidal modulated signal. Modified trapezoidal modulated signal is added the trapezoidal wave on the rectangular wave. γ is the additional ratio of the rectangular wave. When γ= 0, it becomes the trapezoidal waveform and γ=1, the rectangular waveform. The high frequency components included in the waveform can be controlled by γ. The fourier development of the line voltage of the modified trapezoidal modulated inverter is described as Equation 4. [5],[6],[9]

$$V_n = ME_d\left\{\frac{4\gamma}{n\pi}\cos\frac{n\pi}{6} + \frac{24(1-\gamma)}{n^2\pi^2}\sin\frac{n\pi}{6}\right\}\cos\frac{n\pi}{6} \qquad (4)$$

where, $n=6k\pm 1$ (k=0,1,2,…,$n\neq$-1), V_n = amplitude of line voltage, E_d = input DC voltage of inverter, M = ratio of modulation.

The fundamental component of the three-phase sinusoidal modulated inverter is calculated as Equation 5 under same input voltage (E_d) condition.

$$V_1 = M\frac{E_d}{2}\sqrt{3} = 0.866ME_d \qquad (5)$$

Figure.3 shows the output ratio of the fundamental component and the n-th harmonics (V_n/ME_d) of trapezoidal waveform. As shown in Figure3, the output ratio of each component changes by γ. The modified trapezoidal signal has larger fundamental component than the sinusoidal signal. The modified trapezoidal modulated power source is suitable as the power source because it has large output of the fundamental component compared with the sinusoidal modulated inverter and some controllable different frequency component.

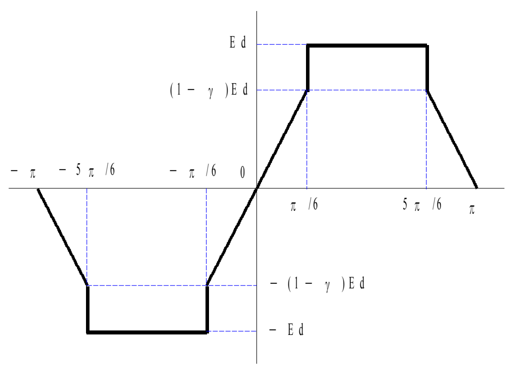


Figure.2 Modified trapezoidal modulated signal

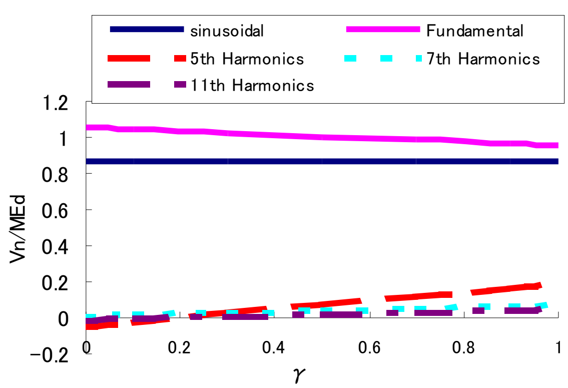


Figure.3 Relation between γ and major frequency components included in output PWM voltage.[5],[6],[9]

Figure.4 shows the generation principle of PWM pulse and the output voltage wave of the modified trapezoidal modulated inverter. The ratio of the modulation (M) is set to be 1. As shown in fig.4, the switching devices in the inverter stop during 240 degree of the period. It causes the reduction of the switching losses in the inverter and the improvement of the efficiency in the whole system. While it is necessary to keep M =1, the output voltage of the inverter has to be controlled by E_d. Therefore, the inverter uses PAM mode. Figure.5 shows three-phase modified trapezoidal waveform compared with the three-phase sinusoidal waveform. As shown in Figure.5, E_d is always shared by each phase in the modified trapezoidal waveform. In other ward, the DC input is used all section. It causes higher utilization of the power source than the sinusoidal modulated inverter. Figure.6 shows the output of the three-phase modified trapezoidal modulated power source. In the three-phase inverter, the switching devices in the each phase also stop during 240 degree of the period.

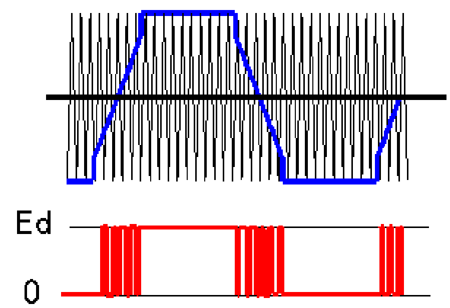


Figure.4 Switching and output waveform of single-phase modified trapezoidal modulated inverter

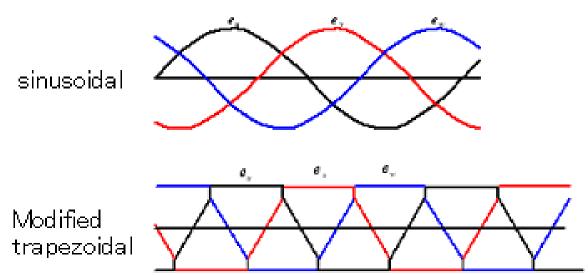


Figure.5 Sinusoidal and modified trapezoidal modulated.

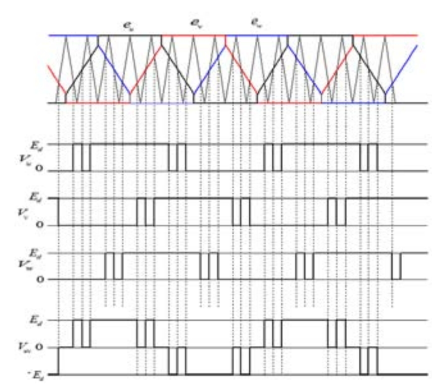


Figure.6 The theory generated PWM pulse of modified trapezoidal

4 EXPERIMENTAL EQEIPMENT

Figure.7 shows the whole experimental systems. PE-EXPERTⅢis used for the switching control of the voltage source inverter as the sinusoidal modulated power source, the power source including the high frequency component, and the modified trapezoidal modulated power source. Under the modified trapezoidal modulated power source operation, PAM mode is used. The semiconductor switching devices are used in AC/DC converter in order to achieve the PAM mode. These switching devices change the DC input voltage to control the output voltage in the inverter. In this experiment set up, the rectifier circuit using the diode bridge is used in the AC/DC converter. The variable transformer is used to control the DC input voltage instead of the semiconductor switching devices. The ratio of modulation (*M*) equals 1. The carrier frequency of the inverter is 10kHz. The cut off frequency of LC filter is set to be 1.5kHz. The protection resistance uses not to be short circuit, when it is driven in the low frequency.

Figure.8 shows the experimental equipment of LIM. Table.1 shows the principal parameter of LIM. The four load cells located beneath the primary side measure the attractive force. The thrust force is measured by two load cells located in front of the primary side. The air gap is 3mm.

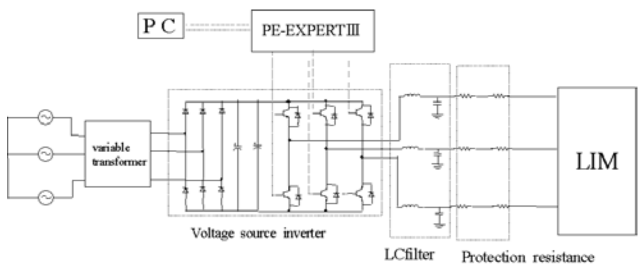
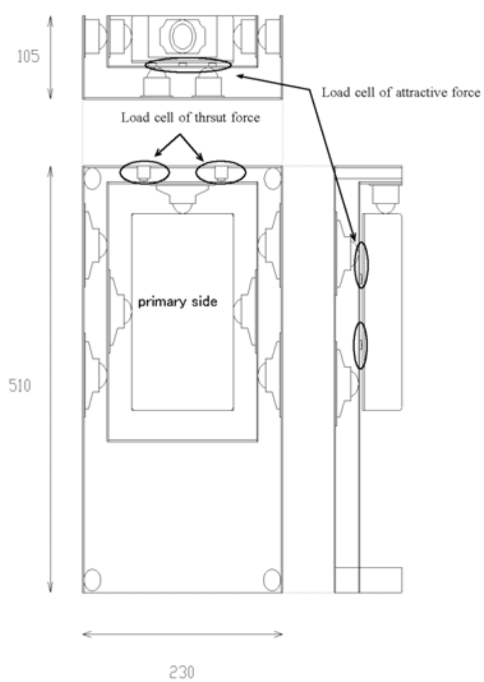


Figure.7 Experimental systems



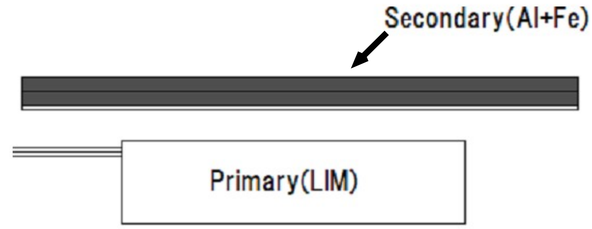


Figure.8 Experimental equipment

Table.1 Principal parameters of LIM

Primary side		
Size	230(l)×150(w)×45(h)	
Weight	5[kg]	
Pole pitch	45	
Pole No.	4	
Nominal	125VAC	24VDC
MAX	5[A]	3[A]
MIN	0.1[A]	
Secondary side		
Size	800(l)×260(w)	
Thickness	Al : 1 + Fe : 9	

5 EXPERIMENTAL RESULTS

5.1 Characteristics of the attractive force and thrust force driven by the power source including the different frequency components

Figure.9 shows the input line voltage, the line input current, and their spectrum results when the LIM is driven by the power source including the high frequency component. The spectrum results indicate that the power source has only two different frequency components. The lower frequency is 10Hz and the higher one is 50Hz. Figure.10, Figure.11 show the characteristics of the attractive force and the thrust force of LIM respectively. As shown in Figure.10 and Figure.11, the total attractive force and the total thrust force are sum of the forces generated by the low frequency component and the high frequency component as derived in Equation 3. The modified trapezoidal modulated output has the fundamental component and some high frequency component as the harmonics. The attractive force and the thrust force driven by the modified trapezoidal modulated power source are also sum of the forces generated by the low frequency component and the harmonics component.

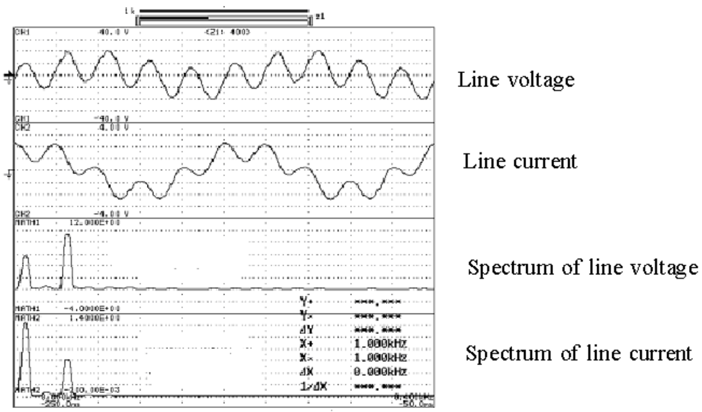


Figure.9 Input wave of LIM

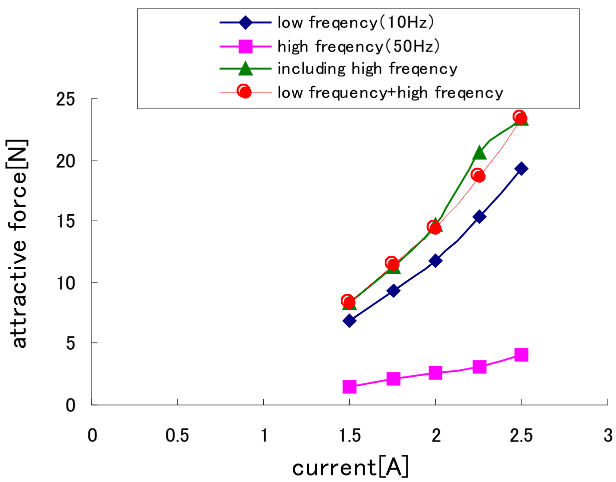


Figure.10 Characteristics of attractive force-current of LIM

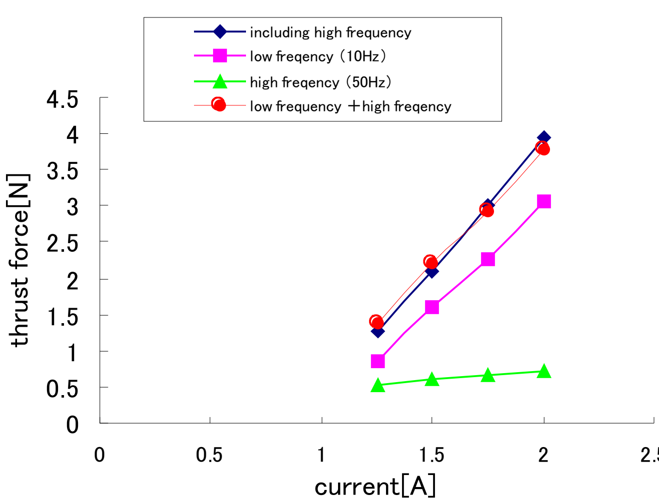


Figure.11 Characteristics of thrust force-current of LIM

5.2 Characteristics of the attractive force and thrust force of LIM driven by the modified trapezoidal modulated power source

Figure.12 shows the output waveforms and their spectrum results of the modified trapezoidal modulated power source in case that the modulated ratio γ is 1 and the fundamental frequency is 30Hz. As shown in Figure 12, the 5th harmonics voltage normalized by the fundamental voltage is 0.178 and the normalized current is 0.063. The 7th normalized harmonics voltage is 0.132, and the normalized current is 0.039. Theoretically the 5th normalized harmonics voltage is 0.200, normalized current is 0.082, the 7th normalized harmonics voltage is 0.083, and the normalized current is 0.026.

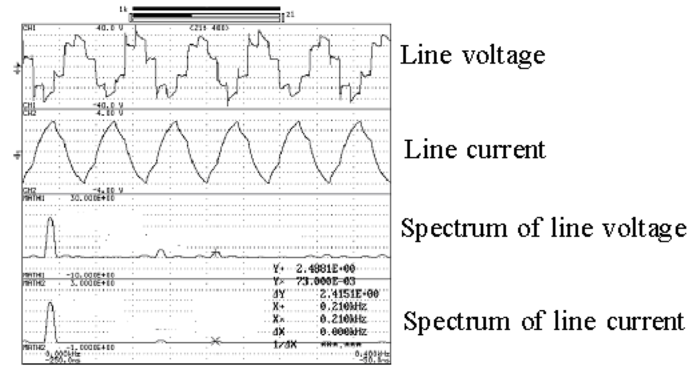


Figure.12 Input wave of LIM [γ=1: rectangular]

Figure.13 and Figure.14 show the output waveforms and their spectrum results in the case of γ=0.5 and γ=0 respectively. In the case of γ=0.5, the 5th normalized harmonics voltage is 0.061, the normalized current is 0.021, the 7th normalized harmonics voltage is 0.073, and the normalized current is 0.0214. In the case of γ=0, the 5th normalized harmonics voltage is 0.060, the normalized current is 0.017, the 7th normalized harmonics voltage is 0.023, and the normalized current is 0.006. These spectrum results indicate that the ratio of harmonics component is changed theoretically by γ.

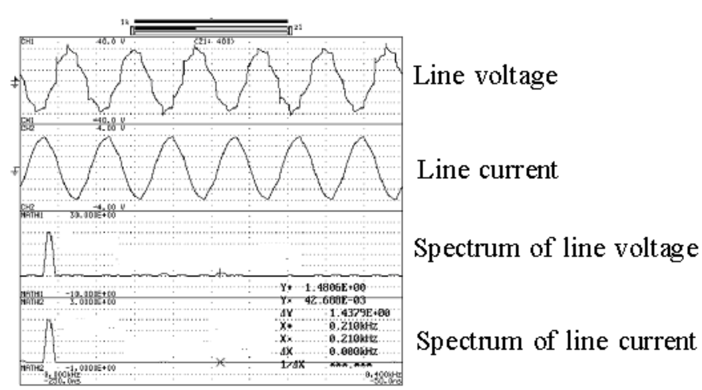


Figure.13 Input wave of LIM [γ=0.5]

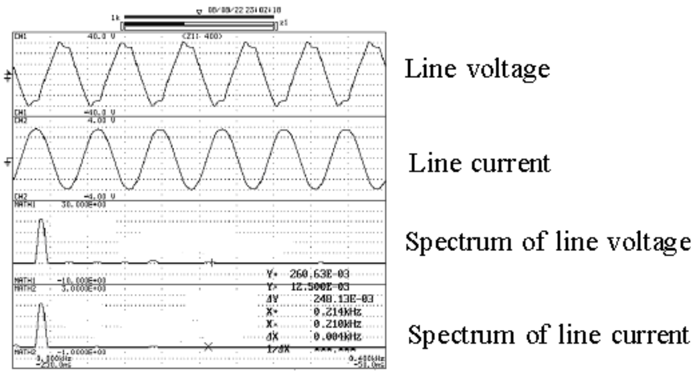


Figure.14 Input wave of LIM [γ=0: trapezoidal]

Figure.15 and Figure.16 show the characteristics of the attractive force and the thrust force, when the input DC voltage of inverter is 50V. The forces are changed according to the additional ratio γ. In every case, the forces are lager than in the case that the sinusoidal modulated inverter is used.

Figure.17 and Figure18 show the characteristics of attractive force and thrust force when the fundamental frequency is 30Hz and γ is changed.

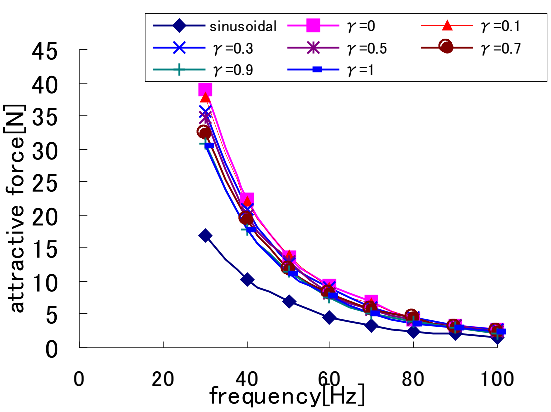


Figure.15 Characteristics of attractive force-slip frequency

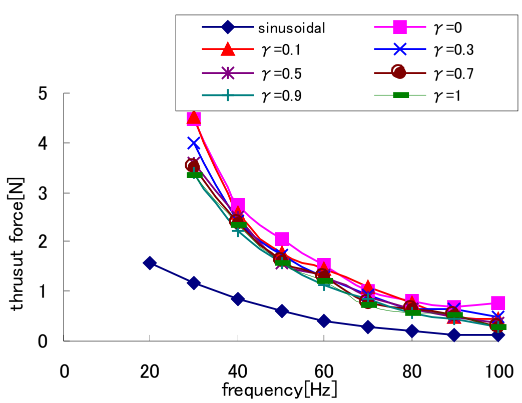


Figure.16 Characteristics of thrust force-slip frequency

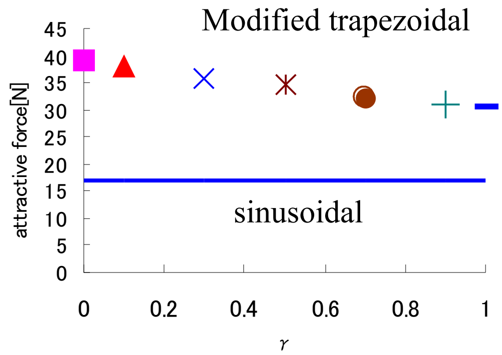


Figure.17 Characteristics of attractive force-γ

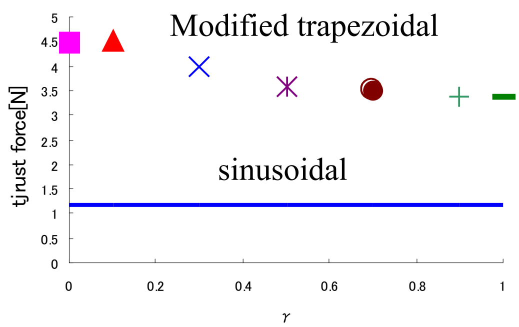


Figure.18 Characteristics of thrust force-γ

As shown in Figure.15 and Figure.16, the attractive force and the thrust force become larger when the additional ratio γ becomes small. These characteristics are similar to the characteristics of the output ratio of the fundamental component of the trapezoidal waveform as shown in Figure 3. Therefore, the forces and the output ratio of the fundamental component are normalized by the forces and the output ratio in the case of γ = 0.

Figure.19 shows the characteristics of V^2/V_0^2 and F_a/F_{a0}-γ where V is the output voltage of the fundamental component, V_0 is the output ratio in the case of γ = 0, F_a is the attractive force, and F_{a0}-γ is the attractive force in the case of γ = 0. Figure.20 shows the characteristics of V^2/V_0^2, and F_t/F_{t0}-γ where F_t is the thrust force, and F_{t0}-γ is the thrust force in the case of γ = 0. Figure.19 and Figure20 show that the attractive force and the thrust force depend on the value of the fundamental component and some high frequency harmonics components hardly affected the forces. As shown in Figure11, Figure 12 and Figure 13, the current of the harmonics is very small. Therefore, it is the reason why the attractive force and the thrust force depend on only the fundamental component.

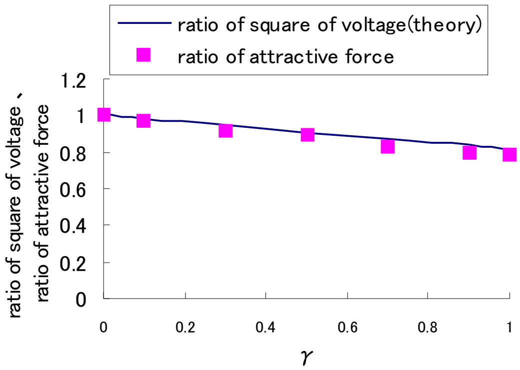


Figure.19 Characteristics of $V^2/V02$, F_a/F_{a0}-γ

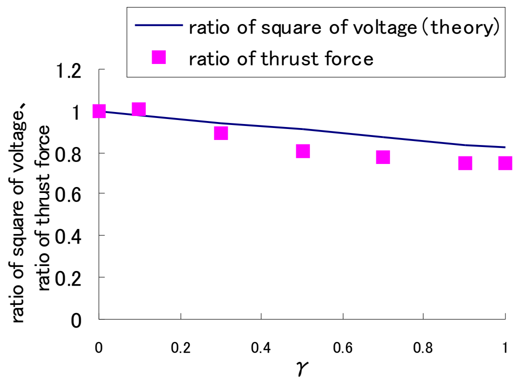


Figure.20 Characteristics of V^2/V_0^2, F_t/F_{t0} -γ

6 CONCLUSION

We propose that the modified trapezoidal modulated power source is used as the power source for the LIM drive. The modified trapezoidal modulated power source has high utilization of the power source, high efficiency because of the small switching losses in the inverter, the larger fundamental component than the sinusoidal modulated inverter in the case of the same input DC voltage and the controllable harmonics components by the addition ratio γ. The modified trapezoidal modulated power source is suitable for our proposed control method using two different frequency components. The characteristic of the attractive force and the thrust force of the LIM are verified by the experimental results when the LIM is driven by the modified trapezoidal modulated power source. The larger attractive force and the larger thrust force are generated compared with the sinusoidal modulated power source. However, the current of the harmonics is very small and the forces generated by the harmonics do not affect the total forces. In this case, the attractive force and the thrust force are controlled by only the fundamental component changed by γ.

When the attractive force and the thrust force of LIM are controlled by the power source including high frequency component, it is necessary to use the modified trapezoidal modulated power source with the current source inverter. It is another solution to use the other modulation signal.

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