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Investigation of Non-sinusoidal Oscillator of Continuous Casting Mold Synchronously Driven by Double Servomotors and Technological Parameters

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Keywords：continuous casting, mold, non-sinusoidal oscillation, technological parameters.

ABSTRACT

In order to adjust the modification ratio of non-sinusoidal oscillation waveform online, a new mechanical oscillator of continuous casting mold synchronous driven by double servomotors was proposed in this paper. Firstly, the rigid-flexible coupled model of oscillator was established. Secondly, the working principle of non-sinusoidal oscillator was analyzed and the model of the oscillator was validated by using dynamics software. Then the non-sinusoidal oscillation waveform function was given and the angular speed of the servomotor was deduced. Besides, by analyzing the parameters of oscillation technology, the calculation method of each oscillation technological parameter was presented, the multi technological parameters curves were given and the control model of casting speed and oscillation frequency was established. Compared with the industrial parameters of sinusoidal oscillation, the synchro-control model of non-sinusoidal oscillation could improve the slab quality. The results of this paper will provide reference for the oscillator optimization and industrial application.

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INTRODUCTION

Mold non-sinusoidal oscillation could produce more reasonable technological parameters, such as, shorter negative strip time, larger negative distance, longer positive strip time and smaller positive strip velocity. Thus, it is one of the key technologies to develop high efficient continuous casting (Li et al.,2000; Lin et al.,2015; Kuo et al.,2015). Shorter negative strip time makes the depth of oscillation marks shallow. Larger negative distance results in larger force to remove slab from mold and helps to weld the cracks in slab shell together. Longer positive strip time and smaller positive strip velocity will melt a larger amount of casting powder, which will result in a better lubricating condition. Therefore, smaller friction force between mold and slab shell reduces the tensile stress of slab shell and cracks in the slab shell. Thereby, non-sinusoidal oscillation can improve surface quality of slab by reducing an amount of micro-cracks in slab shell and shallowing the depth of oscillation marks (Zhang et al., 2011; 2014; CIBULKA et al., 2016; Sathish, R., 2017).

In industry field, there are three kinds of non-sinusoidal oscillation technique to drive the mold, which are hydraulic, servo electric cylinder and mechanical driving (Fang et al., 2014). Although the hydraulic system could realize any waveform and adjust the modification ratio of non-sinusoidal waveform, the frequency and the amplitude online, the investment and maintenance are too expensive. And the system is complicated. For the servo electric cylinder (Tian et al., 2004), the system could also adjust the modification ratio, the frequency and the amplitude online, but frequently changing the rotational direction of servomotor has a bad effect on the service life. Moreover, it is difficult for synchronous control of four electric cylinders to achieve high control precision. The mechanical type of non-sinusoidal oscillator system has the advantages of low investment, simple transmission system, and larger carrying capacity and so on. And it is significant to the new caster and the reforming of existing caster. Several mechanical kinds of oscillators were developed, such as elliptical gears (Liu et al.,2002; Zhang et al.,2004; 2013), double eccentric shafts (Zhang et al.,2005; 2016), non-circular gears (Liu et al.,2013; Yang et al.,2015), anti-parallel four-barlinkage (Zhang et al.,2009; 2010; 2011), cam profile for eccentric shaft (Park et al.,2014). Unfortunately, the modification ratio of mechanical oscillator could not be adjusted online, which limits the quality of the slab to further improve.

In this paper, a non-sinusoidal oscillator synchronously driven by double servomotors was proposed. And its frequency and modification ratio of non-sinusoidal oscillation could be adjusted online. When the oscillator stops, the amplitude can be changed. The mechanism has the advantages of simple driving system, compact structure, low oscillator investment, convenient maintenance and high reliability. What's more, the rigid-flexible coupling model of oscillator was established, which was illustrated through dynamics software. In addition, the non-sinusoidal waveform was given and the calculation methods of the technical parameters were deduced. Meanwhile, the non-sinusoidal control model between casting speed and oscillation frequency was optimized and provides reference for the industry application.

MECHANISM OF NON-SINUSOIDAL OSCILLATIOIN FOR MOLD

Working principle of non-sinusoidal oscillation system

The non-sinusoidal oscillation system of mold synchronously driven by double servomotors is composed of driving, guiding leaf springs, buffer springs, oscillating table and mold, shown in Fig.1. To describe the working principle, the half model of the oscillator is studied because of the system's symmetry, presented in Fig.2. From Fig.2, the planetary reducer connecting with the eccentric shaft is driven by the servomotor. While the servomotor rotational speed changes at a special rule, the planetary reducer and eccentric shaft are non-uniform rotation. So the non-sinusoidal oscillation rules of point *S* are developed. Then the linkage is pushed by eccentric shaft. With leaf and buffer springs, the oscillating table and mold driven by linkage and move up and down.

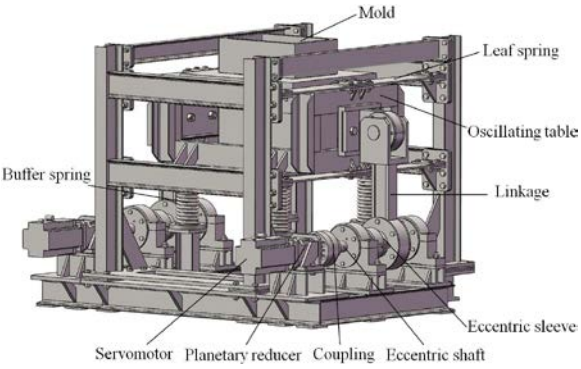

Fig. 1. Mechanical oscillator model.

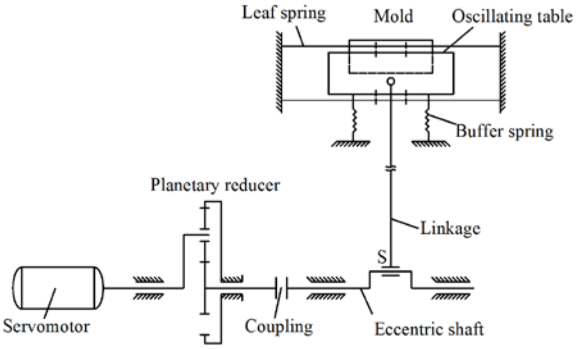

Fig. 2. Working principle diagram of non-sinusoidal oscillator.

Kinetic analysis

The compound functions of non-sinusoidal oscillation waveform are given as follows (Zhang et al., 2016).

The displacement function is

$$s = mh\left(\sin(2\pi ft) + k\sin(4\pi ft)\right) \tag{1}$$

The velocity function is

$$v = 2\pi fmh\left[\cos(2\pi ft) + 2k\cos(4\pi ft)\right] \tag{2}$$

The acceleration function is

$$a = -4\pi^2 f^2 mh\left[\sin\left(2\pi ft\right) + 4k\pi f\sin(4\pi ft)\right] \tag{3}$$

The modification ratio α is one of the main parameters for non-sinusoidal oscillation waveform. Based on the non-sinusoidal oscillation characteristic, the peak time of non-sinusoidal displacement lags behind the sinusoidal displacement, shown in Fig. 3. So the modification ratio α of non-sinusoidal can be defined as

$$\alpha = 4f\Delta T \tag{4}$$

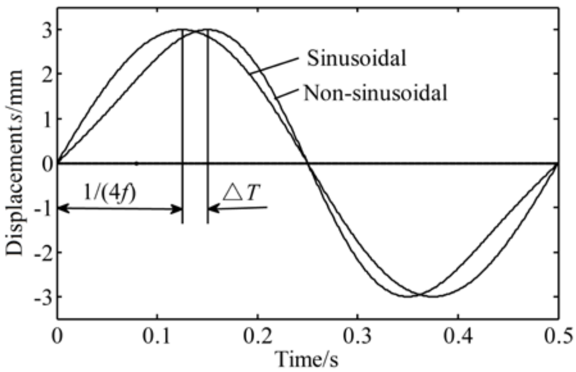

Fig. 3. Sinusoidal and non-sinusoidal oscillation waveform.

When the mold arrives at the peak time $\frac{1+\alpha}{4f}$ of non-sinusoidal oscillation waveform, k and m can be computed as follows.

At the peak time, the oscillation velocity of mold is 0. And Eq. (2) can be expressed as

$$2\pi fmh\left\{\cos\left[\frac{\pi}{2}(1+\alpha)\right]+2k\cos\left[\pi(1+\alpha)\right]\right\}=0 \quad (5)$$

Then, k is obtained as

$$k=-\frac{\sin\left(\frac{\alpha\pi}{2}\right)}{2\cos(\alpha\pi)} \quad (6)$$

To proceed, the oscillation displacement h of mold can be obtained from Eq. (1)

$$h=mh\left\{\sin\left[\frac{\pi}{2}(1+\alpha)\right]+k\sin\left[\pi(1+\alpha)\right]\right\} \quad (7)$$

In a period [0, $\frac{1}{f}$], then submitting Eq. (6) in to (7),

$$1=m\left\{\sin\left[\frac{\pi}{2}(1+\alpha)\right]-\frac{\sin\left(\frac{\alpha\pi}{2}\right)}{2\cos(\alpha\pi)}\sin\left[\pi(1+\alpha)\right]\right\} \quad (8)$$

$$m=\frac{\cos(\alpha\pi)}{\cos^3\left(\frac{\alpha\pi}{2}\right)} \quad (9)$$

The longitudinal displacement of the linkage can be expressed as

$$s_1=e\sin(\omega t) \quad (10)$$

The angular speed of the eccentric shaft can be calculated since the longitudinal displacement of the linkage is consistent with the mold displacement, shown in Fig. 4. When the s_1 is equal to s, the angular speed ω of the eccentric shaft is determined. Since the eccentric shaft rotates in a single direction, then

$$\omega=\left|\frac{v}{\sqrt{e^2-s^2}}\right|=\left|\frac{2\pi fm\left[\cos(2\pi ft)+2k\cos(4\pi ft)\right]}{\sqrt{1-\left[m\left(\sin(2\pi ft)+k\sin(4\pi ft)\right)\right]^2}}\right| \quad (11)$$

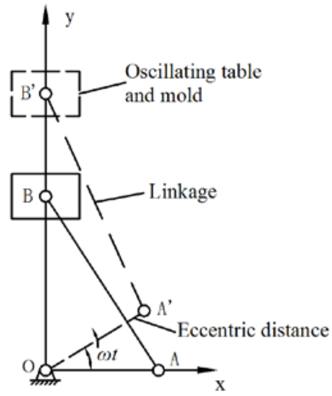

Fig. 4. Sketch of eccentric shaft driving mechanism.

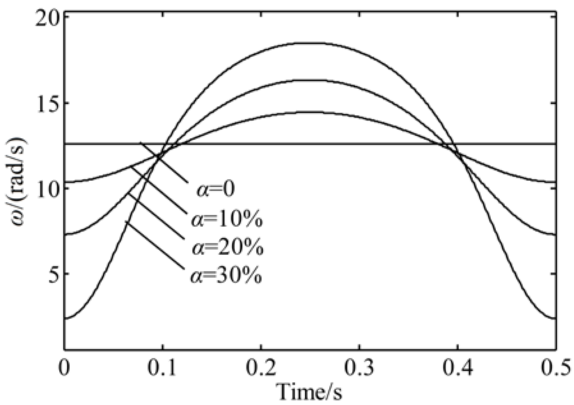

Fig. 5. Angular speed of eccentric shaft with different modification ratios.

Fig. 5 is the eccentric shaft angular speed of different modification ratios, which can realize the compound function of non-sinusoidal oscillation waveform. The non-sinusoidal oscillation waveform can be obtained as long as the eccentric shaft is rotated according to certain law. Besides, the rigid-flexible coupling model of oscillator is established. Furthermore, non-sinusoidal oscillation waveform is simulated. When the modification ratio α=20.5%, the frequency f=2Hz, the amplitude h=5mm, the mold oscillation waveform is shown in Fig.6 to verify the working principle.

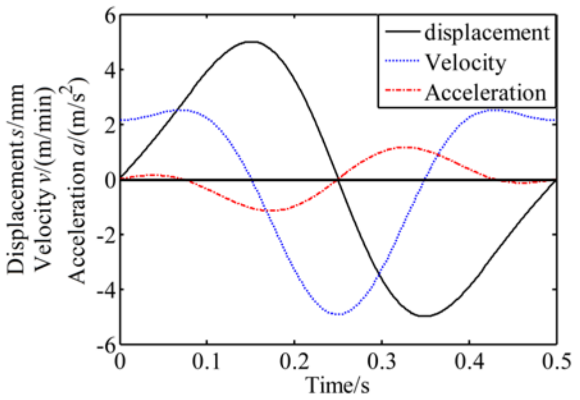

Fig. 6. Oscillation waveform of compound function.

TECHNOLOGICAL PARAMETERS OF NON-SINUSOIDAL OSCILLATION

Negative Strip Time. Negative strip time is the period of time during which the mold moves downward with a higher speed in comparison to the casting speed. Velocity curve of non-sinusoidal oscillation is shown in Fig. 7.

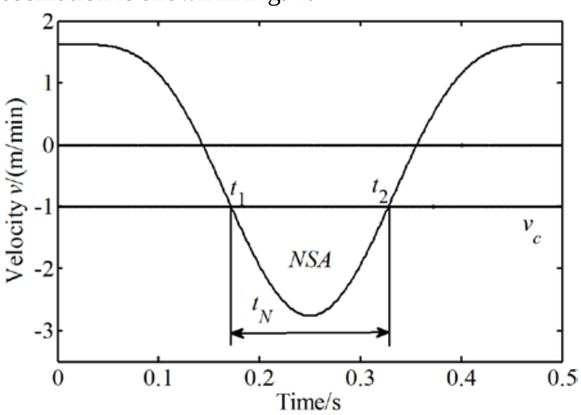

Fig. 7. Velocity curve of non-sinusoidal oscillation.

In Fig. 7, t_N and t_1 are

$$t_N = 2\left(\frac{1}{2f} - t_1\right) \tag{12}$$

$$t_1 = \frac{1}{2f} - \frac{t_N}{2} \tag{13}$$

Submitting Eq. (13) into Eq. (2), then

$$v_c = 2\pi fmh\left[\cos(\pi - \pi f t_N) + 2k\cos(2\pi - 2\pi f t_N)\right] \tag{14}$$

$$t_N = \frac{1}{\pi f}\cos^{-1}\left(-\frac{\cos(\pi\alpha)}{4\sin(\frac{\pi\alpha}{2})} - \sqrt{\frac{\pi hf\cos^2(\pi\alpha) + 4v_c\sin(\frac{\pi\alpha}{2})\cos^3(\frac{\pi\alpha}{2})}{16\pi hf\sin^2(\frac{\pi\alpha}{2})} + \frac{1}{2}}\right) \tag{15}$$

When α equals 20%, the velocity function in Eq. (2) becomes

$$v = 5.909\, fh\left[\cos(2\pi ft) - 0.382\cos(4\pi ft)\right] \tag{16}$$

From Eq. (14), it can be obtained as

$$v_c = -5.909\, fh\left[\cos(\pi f t_N) + 0.382\cos(2\pi f t_N)\right] \tag{17}$$

The negative strip time curve can be obtained from Eq. (17) with different values of Z, where $Z = \frac{100h}{3v_c}(\mathrm{mm \cdot min/m})$, and the curve is shown in Fig. 8.

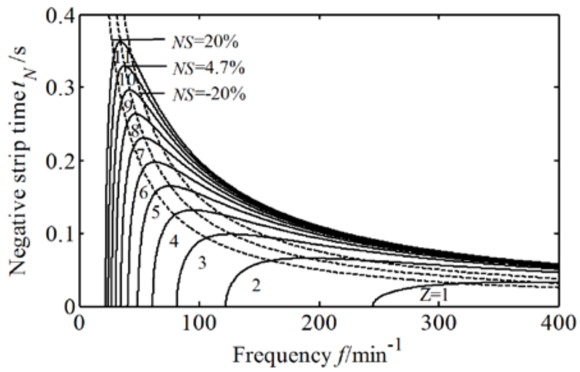

Fig. 8. Negative strip time curve.

Negative Strip Ratio. Negative strip ratio is the ratio between the difference of casting speed and downward average speed of mold and casting speed, which can be defined as

$$NS = \frac{v_c - \bar{v}_m}{v_c} \times 100\% \tag{18}$$

For the non-sinusoidal oscillation, NS can be expressed as

$$NS = 1 - 4fh / \left[(1-\alpha)v_c\right] \tag{19}$$

From Eq. (15) and Eq. (19), the relationship between NS and t_N can be expressed as

$$t_N = \frac{1}{\pi f} arc\cos\left(\frac{1 - \sqrt{1 - 16k\left(\frac{2\cos^3(0.5\pi\alpha)}{\pi(1-\alpha)(1-NS)} - 2k\right)}}{8k}\right) \tag{20}$$

When the *NS* is constant, the relationship between f and t_N is presented in Fig.8.

Negative strip distance. During the negative strip time, the displacement of mold moving downward relatively to the slab is negative strip distance (the area, shown in Fig.7). *NSA* can be defined as

$$NSA=\int_{t_1}^{t_2}\left|v_m-v_c\right|dt=2\int_{T/2-t_N/2}^{T/2}\left|v_m-v_c\right|dt$$
$$=2h\frac{\cos(\pi\alpha)}{\cos^3(\frac{\pi\alpha}{2})}\left(1+\frac{\sin(\frac{\pi\alpha}{2})}{2\cos(\pi\alpha)}\right)\sin(2\pi ft_N)+v_ct_N \tag{21}$$

Negative strip time ratio. Negative strip time ratio is the ratio between negative strip time and half of a period.

$$NSR=\frac{t_N}{0.5T}=2ft_N$$
$$=\frac{2}{\pi}\cos^{-1}\left(-\frac{\cos(\pi\alpha)}{4\sin(\frac{\pi\alpha}{2})}-\sqrt{\frac{\pi hf\cos^2(\pi\alpha)+4v_c\sin(\frac{\pi\alpha}{2})\cos^3(\frac{\pi\alpha}{2})}{16\pi hf\sin^2(\frac{\pi\alpha}{2})}+\frac{1}{2}}\right) \tag{22}$$

Positive strip time. Positive strip time t_p is the period of time during which the mold moves upward relative to the slab in a single oscillating cycle, and it can be expressed as

$$t_p=\frac{1}{f}-t_N$$
$$=\frac{1}{f}-\frac{1}{\pi f}\cos^{-1}\left(-\frac{\cos(\pi\alpha)}{4\sin(\frac{\pi\alpha}{2})}-\sqrt{\frac{\pi hf\cos^2(\pi\alpha)+4v_c\sin(\frac{\pi\alpha}{2})\cos^3(\frac{\pi\alpha}{2})}{16\pi hf\sin^2(\frac{\pi\alpha}{2})}+\frac{1}{2}}\right) \tag{23}$$

Then Eq. (17) becomes

$$v_c=5.909\,fh\left[\cos\left(\pi\,ft_p\right)\text{-}0.382\cos\left(2\pi\,ft_p\right)\right] \tag{24}$$

A group of curves of positive strip time could be obtained with different values of t_p, shown in Fig.9.

Positive strip velocity. The positive strip velocity Δv is the velocity difference between the maximum velocity of mold moving upward and the casting speed. That is

$$\Delta v=v_{u\max}+\left|v_c\right| \tag{25}$$

When α equals 20%, the derivative of the Eq. (2) is zero, then the maximum of the velocity is

$$v_{u\max}=4.191\,fh \tag{26}$$

$$v_c=\Delta v-4.191\,fh \tag{27}$$

When h equals 3.5mm, a group of curves of positive strip velocity are given in Fig. 9 with different values of Δv.

Curves for Multi-parameters. In order to determine the synchro-control model of casting speed and oscillation frequency, the curve for multi technological parameters is demonstrated. Non-sinusoidal oscillation technological parameters of t_N, t_p, *NS* and Δv are illustrated in Fig.9

According to Eq. (20), a group of negative strip ratio curves with different values of *NS* could be obtained, shown in Fig. 9. When *NS* equals 38.81%, t_N equals zero. When *NS* equals 38.81% or bigger, there will be no negative strip time. When synchro-controlling model of casting speed and oscillation frequency is determined for different kinds of steel, by using Fig. 9, the rationalities of multi-parameters could be simultaneously taken into account.

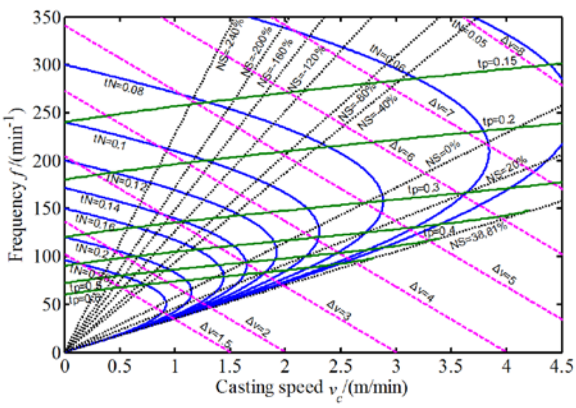

Fig. 9. Multi-parameters curves of non-sinusoidal oscillation with α=20% and h=3.5mm.

OPTIMIZATION AND DISUSSION

In China, the parameters of a steel plant are using to produce the steel, shown in Table 1.

Table 1. Caster parameters..

Item	Unit	Value
Slab section size	mm×mm	180×1800
Oscillation mode		Sinusoidal
Oscillation amplitude	mm	±4
Oscillation frequency	min^{-1}	104
Casting speed	m/min	1.15

In order to improve the slab quality, the synchro-control model of non-sinusoidal oscillation is optimized according to the Fig. 9 as follows.

$$f = \begin{cases} 75 & v_c < 0.7 \\ 70v_c + 26 & v_c \geq 0.7 \end{cases} \tag{28}$$

And the oscillation technological parameters are illustrated in Table 2.

Table 2. Control model parameters of non-sinusoidal oscillation.

v_c (m/min)	f (min^{-1})	t_N (s)	NS (%)	NSA (mm)	NSR (%)	t_p (s)	$\triangle v$ (m/min)
0.3	75	0.286	-337.5	5.486	71.53	0.514	1.4
0.4	75	0.275	-228.13	5.018	68.81	0.525	1.5
0.5	75	0.264	-162.5	4.568	66.11	0.536	1.6
0.6	75	0.254	-118.75	4.136	63.44	0.546	1.7
0.7	75	0.243	-87.5	3.722	60.77	0.557	1.8
0.8	82	0.219	-79.38	3.595	59.92	0.513	2.003
0.9	89	0.2	-73.06	3.489	59.2	0.475	2.205
1.0	96	0.183	-68	3.4	58.59	0.442	2.408
1.1	103	0.169	-63.86	3.322	58.06	0.413	2.611
1.15	106.5	0.163	-62.07	3.288	57.83	0.401	2.712
1.2	110	0.157	-60.42	3.256	57.6	0.388	2.814
1.3	117	0.147	-57.5	3.198	57.2	0.366	3.016
1.4	124	0.138	-55	3.147	56.83	0.346	3.219
1.5	131	0.129	-52.83	3.102	56.51	0.329	3.422

Note: α=20%, h=3.5mm.

Table 3 shows that under the same casting speed, the negative strip time and the positive strip velocity of the non-sinusoidal oscillation are smaller than those of sinusoidal oscillation. So the depth of the oscillation marks will become shallow and the friction of the slab and mold will reduce. The negative strip distance of the non-sinusoidal oscillation is larger than that of sinusoidal oscillation, which is helpful to weld the cracks in solidified shell together. The positive strip time of non-sinusoidal oscillation is longer than that of sinusoidal oscillation, which will result in a better lubrication condition with a larger amount of casting powder, reduce the tension stress and minimize cracks of solid shell. Therefore, non-sinusoidal oscillation could improve surface quality by smoothing the slab surface and reducing the amount of micro-cracks in slab shell, and decrease the probability of steel breakout.

Table 3. Oscillation technological parameters of sinusoidal and non-sinusoidal.

Oscillation mode	Casting speed(m/min)	t_N (s)	NSA (mm)	$\triangle v$ (m/min)	t_p (s)
Sinusoidal	1.15	0.205	3.259	3.764	0.372
Non-sinusoidal	1.15	0.163	3.288	2.712	0.401

CONCLUSIONS

A new mechanical oscillator driven by double servomotors is proposed, which is suitable for arc and straight-arc type casters. For the proposed scheme, not only the investment is lower, but also the maintenance and manufacturing of oscillator are simpler. Moreover, it is convenient to adjust the modification ratio of non-sinusoidal oscillation waveform online by synchronously controlling angular speed of double servomotors. Non-sinusoidal oscillation control model between oscillation frequency and casting speed is proposed. By this control model, the seasonable technological parameters could be obtained. And the non-sinusoidal oscillation technological parameters are superior to that of sinusoidal oscillation. So the slab surface quality could be improved.

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NOMENCLATURE

s oscillation displacement(mm)

m, k modification coefficient

h oscillation amplitude(mm)

f oscillation frequency(Hz)

t time(s)

v non-sinusoidal oscillation velocity(mm/s)

a non-sinusoidal oscillation acceleration(mm/s^2)

α modification ratio of non-sinusoidal oscillation(%)

ΔT lagging time(s)

s_1 displacement of the longitudinal linkage(mm)

e eccentric distance of eccentric shaft(mm)

ω angular speed of the eccentric shaft(rad/s)

t_N negative strip time(s)

v_c casting speed(mm/s)

NS negative strip ratio(%)

$\overline{v}_m$ downward average speed of mold(mm/s)

NSA negative strip distance(mm)

NSR negative strip time ratio(%)

t_p positive strip time(s)

Δv positive strip velocity(mm/s)

$v_{u\max}$ maximum velocity of mold moving upward(mm/s)

雙伺服電機同步驅動連鑄結晶器非正弦振動裝置及工藝參數研究

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摘 要

為線上調節非正弦振動的波形偏斜率，提出一種新型雙伺服電機同步驅動連鑄結晶器的機械式振動裝置。首先建立振動裝置的剛柔耦合模型；其次分析裝置的工作原理，並進行動力學模擬。給出非正弦振動的波形函數，推導了電機的角速度，此外通過分析振動工藝參數，給出每種工藝參數的計算方法，繪製了多工藝參數等值曲線，製定拉坯速度隨頻率的同步控制模型。與工業應用的正弦振動工藝參數相比，非正弦振動的同步控制模型能够提高鑄坯質量，該研究結果將為振動裝置的優化及工業應用提高參攷。