Measurement of Dynamic Characteristics of Arc Sensor in GMA Welding in Dip Transfer Mode†

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Abstract

The experimentally measured results of the dynamic characteristic of the arc sensor in GMA welding in dip transfer mode are introduced in this paper, where the dynamic characteristic of the sensor is expressed by a set of a sensitivity-frequency characteristic and a phase-frequency characteristic. In order to effectively remove the noise imposed on the detected welding electric signals, authors used the data-processing techniques of FIR digital low-pass filtering and DFT method. The obtained results show that the arc sensors sensitivities are quite higher than that in an open arc welding. It is made clear that this is due to the short-circuiting happened in the welding process, the higher is the short-circuiting frequency, the lower the sensitivities of the arc sensor become. Moreover, the arc sensor's current sensitivity reaches the highest level at around 3 Hz and the SN ratio in current seems to be also the best at 3 Hz. However, the arc sensor's voltage sensitivity increase with frequency increasing in principle, but it's SN ratio is quite poorer than that of current. It has been also clarified that the arc sensors current phase delays but the voltage phase advances relative to the variation of the torch height but the phase delay of current and the phase advance of voltage all do not exceed 180 degree according to experiments.

KEY WORDS: (Arc sensor) (Dynamic characteristic) (Sensitivity) (Phase) (SN ratio) (Frequency) (GMA welding) (Dip transfer mode) (Shielding gas)

1. Introduction

The welding process in dip transfer mode is often used when welding current is less than about 200A. Rather than a steady DC welding process, welding in dip transfer mode is characterized by alternate changes between arc burning and short-circuiting periods. This, consequently, makes both the welding current and the welding voltage vary violently.

On the other hand, the arc sensor is widely used in seam tracking during automatic welding[1]. Its basic principle can be considered as a recognition technique for the variation of the torch height based on the changes of the welding current and/or voltage during welding. Therefore, the extraction of information about the torch height (variation) from the violent varying signals of welding current and voltage becomes a more difficult problem for developing the arc sensor for welding in dip transfer mode by comparison with an open arc welding process.

In a previous report, authors have described an experimental investigation of the dynamic behavior of the arc sensor in the welding in dip transfer mode[2]. That study has given us an understanding of the relation between variations of the torch height and the characteristic parameters such as short-circuiting frequency, maximum and minimum values in one cycle period, arc burning duration and short-circuiting duration. The present study, however, is focused on an understanding of the dynamic relations between the variations of the torch height and the fundamental wave components in the welding current and the welding voltage. In order to extract the fundamental component signal from the detected welding electric signals, FIR (Finite Impulse Response) digital low-pass filtering technique and DFT (Digital Fourier Transformation) methods are used in the study. Having shown the measured results of the dynamic characteristics of the arc sensor, some discussion and approximate simulation analyses are made.

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2. Experimental apparatus and welding conditions

Figure 1 shows the experimental apparatus used in present study. The welding current is supplied by a transistorized power source with a static I-U (current-voltage) characteristic adjustable from CC (Constant Current output) to CP (Constant Potential output). The power source is equipped with an electric reactor which can provide an equivalent inductance (0~600 mH) to control the variation rate of the welding current so as to obtain a stable GMA welding process. According to shielding gases used in experiments, the equivalent inductance of the reactor was set as shown in **Table 1**. The variation of the torch height is controlled by a specially designed up-down oscillator of torch height which can force the torch height to change as a sinusoidal variation wave form with a frequency adjustable from 0~50 Hz and an amplitude (peak to peak) adjustable from 0~5 mm. The wave form variation of the torch height and the responses of the welding current and voltage are simultaneously recorded by a multi-channel digital recorder and then transfered to a personal computer for data-processing.

Welding runs arc on a plate in the down-hand position. The work-piece is mild steel (SM400-900) and its size is 500x100x12 mm^3. The wire electrode is 1.2 mm diameter steel (MIX-50S). The feeding rate of the electrode is set at 86.8 mm/s and the torch height at theoperating point is set at 20 mm for all runs (corresponding average welding current is about 190~200 A). Shielding gases used are shown in Table 1 and their flow rates are the same, 20 l/min. Welding speed is set at 300 mm/min for all runs.

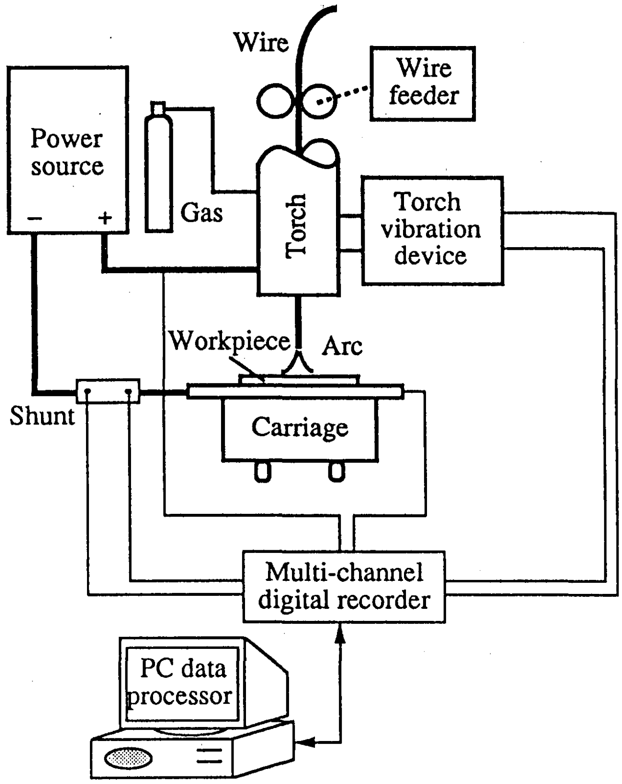


Fig.1 Schematic diagram of experimental apparatus used in this study

Table 1 Setting values of inductance and average welding voltage for the welding in dip transfer mode

Setting Parameter \ Shielding gas	Ar	Ar+ 10%CO_2	Ar+ 20%CO_2	CO_2
Inductance Ls (mH)	0.3	0.26	0.26	0.3
Average welding voltage $\overline{Ut}$ (V)	19.5	18.8	18.8	22.7

Note: Average welding current 190~200A

3. Experimental results

On the basis of control theory, the dynamic characteristic of a system can be expressed by its frequency characteristic, which can be further expressed by an amplitude-frequency characteristic and a phase-frequency characteristic, the former describes the relation between the amplitude ratio of output/input of a sensor and frequency and the latter describes the relation between the output-input phase difference and frequency when the input and the output simultaneously vary as sinusoidal wave forms[3]. The dynamic characteristics of the arc sensor were therefor measured in experiments based on above theory too.

3.1 Real time wave forms

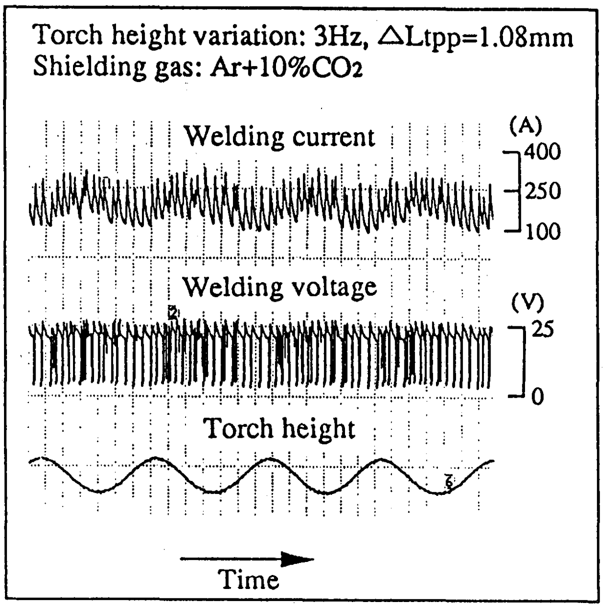


Fig.2 A typical real time wave forms of welding current and voltage in the welding in dip transfer mode under the condition of sinusoidal variation in torch height

Figure 2 shows the typical real time wave forms of the welding current and the welding voltage, where the torch height (the input of the arc sensor) was forced to vary as a sinusoidal wave form during welding. It is seen from the welding current signal that there is a fundamental variation component with a frequency the same as the variation of the torch height. The phenomenon normally happens in welding using a welding power source with a CC characteristic output. The same phenomenon must happen too in the welding voltage although it is difficult to identify without the help of some scientific analysis , as seen in Fig. 2.

Because the arc sensor is based on the fundamental components hidden in the welding current and the welding voltage, we here used an FIR low-pass filter to try to isolate them from detected raw data. **Figure 3** shows an example of the processed results, where Fig. 3(a) is the results for the welding shielded by pure Ar and Fig. 3(b) is for the welding shielded by mixed gas of Ar+10%CO_2 Torch height variation set is the same with a frequency of 3 Hz and amplitude (peak to peak) 1.08 mm. Moreover, the solid lines in Fig. 3 represent the filtered results. It can be observed from the fundamental components that the current signal delays but the voltage signal advances by comparison with the variation of the torch height. Another fact demonstrated by the results is that noise in the voltage signal is much more significant than in the current signal, this suggests that the reliability of an arc sensor using current signal may be much better than one using voltage signal during welding in dip transfer mode.

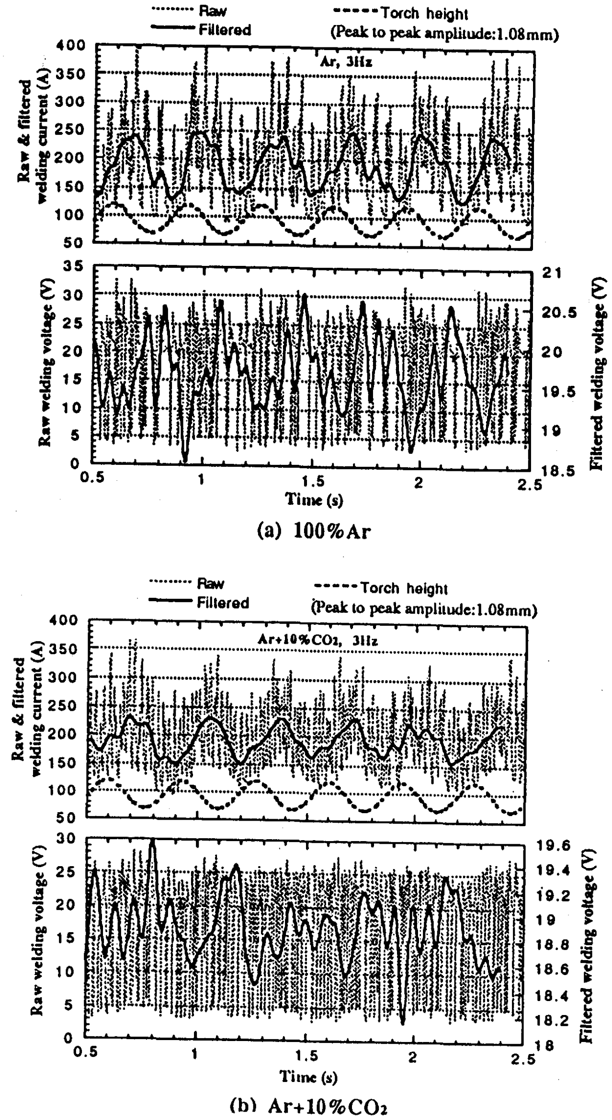


Fig.3 Wave forms of arc sensor's outputs extracted by FIR digital low-pass filter from the welding current and voltage in the welding in dip transfer mode

3.2 Frequency Characteristics

In this section, the DFT method is used instead of an FIR low-pass filter to process the detected signals of the welding current, the welding voltage and the torch height so as to get the exact values of amplitude ratios and phase difference between the output and the input of the arc sensor. **Figure 4** shows an example of the processed results, where only the amplitude spectra of current and voltage wave forms (corresponding to Fig. 3(a)) are being displayed. It is seen from the figure that the relative strength of the fundamental component (about 5 Hz in the case) to other components in the welding current is much higher than in the case of the welding voltage. This fact explains why the SN ratio of the welding current is much better than that of the welding voltage when these are

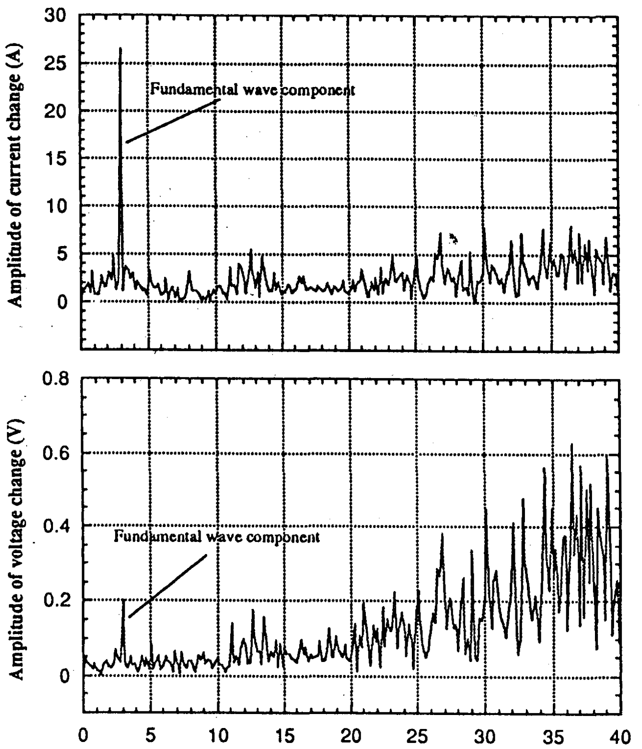


Fig.4 Amplitude spectra of the welding current and voltage in the welding in dip transfer mode

processed by a low-pass filter.

Therefore, the amplitude ratios of output/input of the arc sensor can be calculated by taking their amplitudes at the fundamental frequency. The phase difference can also be obtained from their phases at the fundamental frequency. **Figure 5** and **Figure 6** summarize these results, where the variation amplitude (peak to peak) of the torch height was set at 1.08 mm, 1.53 mm and 2.08 mm respectively for each kind of shielding gas. For a sensor, the amplitude ratio of output/input can be considered as its sensitivity, so we here used the term sensitivity and the amplitude-frequency characteristic is correspondingly called as sensitivity-frequency characteristic, or sensitivity characteristic. Based on the results in Figs. 5 and 6, some features on the characteristics may be summarized as:

(1) The sensitivities, especially the current sensitivity of the arc sensor, are significantly greater than those in welding in the spray transfer mode.

(2) The current sensitivity of the arc sensor greatly depends on the variation frequency of torch height. The sensitivity rapidly increases with increasing frequency in the range less than about 3 Hz. However, it decreases slightly at about 3~5 Hz, but increases again when the frequency exceeds about 5 Hz.

(3) The voltage sensitivity also shows a frequency dependence. In principle it increases with the increasing frequency but it slightly decreases or keeps almost constant in the frequency range of about 3~4 Hz.

(4) The sensitivities of the arc sensor are the highest when welding using purer Ar rather than its mixed gases, which is also different from the arc sensor when welding in spray transfer mode.

The features of the phase characteristic of the arc sensor, may be summarized as:

(5) The current phase of the sensor is delayed by comparison with the torch height variation. The current phase's delay decreases with the frequency, increasing when the frequency is less than about 2 Hz. However, it increases in the frequency range of about 2~4 Hz and it almost does not change when the frequency exceeds about 4 Hz.

(6) The voltage phase of the sensor is advanced by comparison with the torch height. The voltage phase's advance rapidly decreases with the increasing frequency in the range about 2~4 Hz, but it makes almost no change when the frequency exceeds 4 Hz.

Concerning the effect of the variation amplitude of the torch height,

(7) It can be considered that there is almost no effect on the values of the dynamic characteristics of the arc sensor.

4. Discussion

4. 1 Effect of short-circuiting frequency

The electric field intensity E_a in an arc column is well known to depend strongly on the shielding gas composition, E_a being normally higher when using the mixed gases of Ar and CO_2 than when using pure Ar[4, 5]. On the other hand, the sensitivity of the arc sensor in open arc welding is known to increase with increasing Ea[6]. Consequently, the sensitivities of the arc sensor in the welding using mixed gases of Ar and CO_2 can be expected to be higher by comparison with pure Ar.

However, the arc sensor in welding in dip transfer mode does not follow the above prediction, according to the results shown in Figs. 5 and 6. This suggests that the arc sensor in welding in dip transfer mode must be affected by some other important factors.

By observing Fig. 3, it is not difficult to see that the short-circuiting frequency when welding using pure Ar is obviously lower than that when welding using mixed gases of Ar+10%CO_2. To analyze the amplitude-spectrum of the welding current in time the torch height is kept constant, and it is known that the frequency of the main short-circuiting component is about 20~25 Hz for pure Ar, 45~50 Hz for Ar+10%CO_2, 45~50 Hz for Ar+20% CO_2 and 30~35 Hz for 100%CO_2, (where the stated main short-circuiting component refers to that which possesses the highest level of power in the spectrum). Comparing these with the results of Fig. 5, it is not difficult to see that the short-circuiting frequency

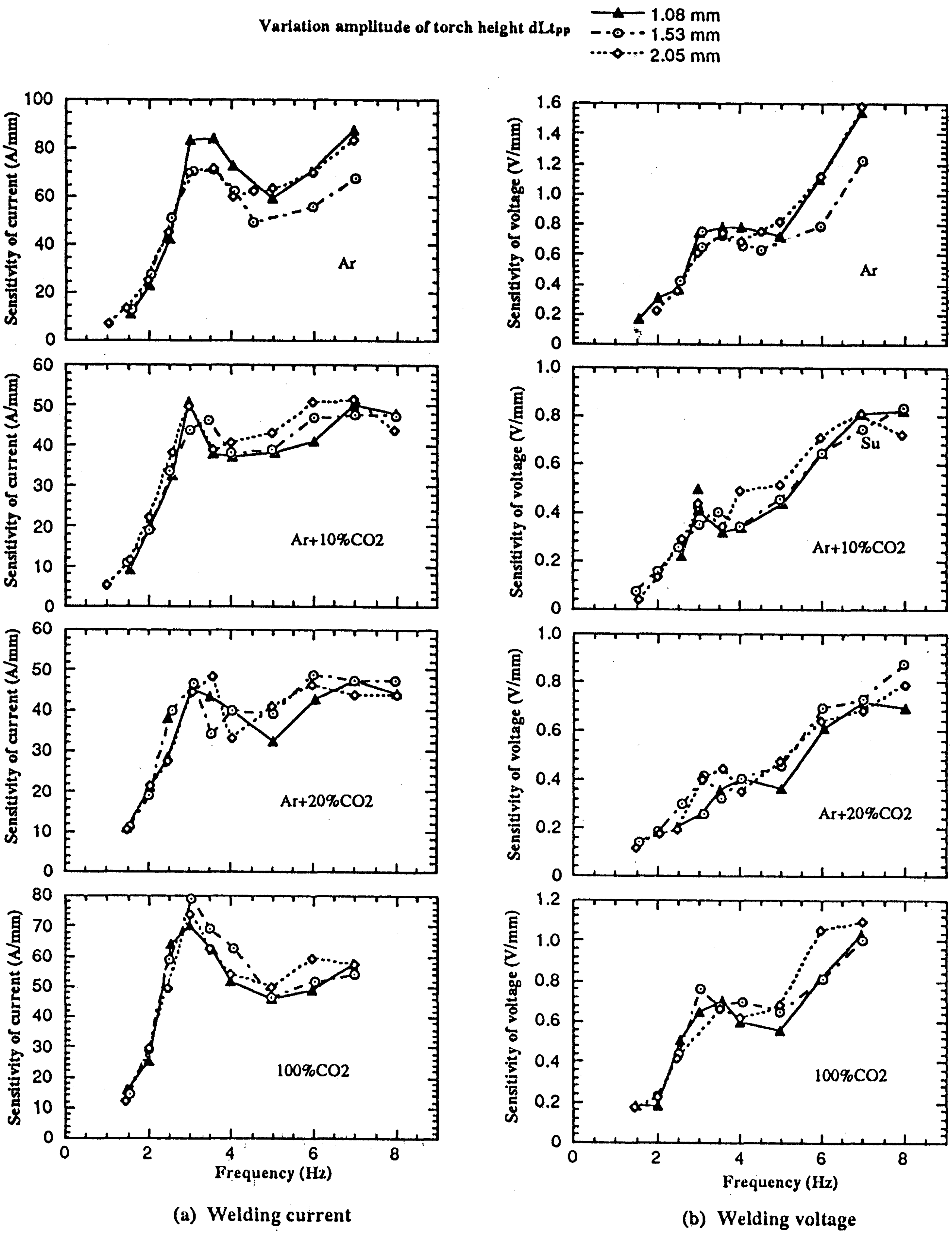
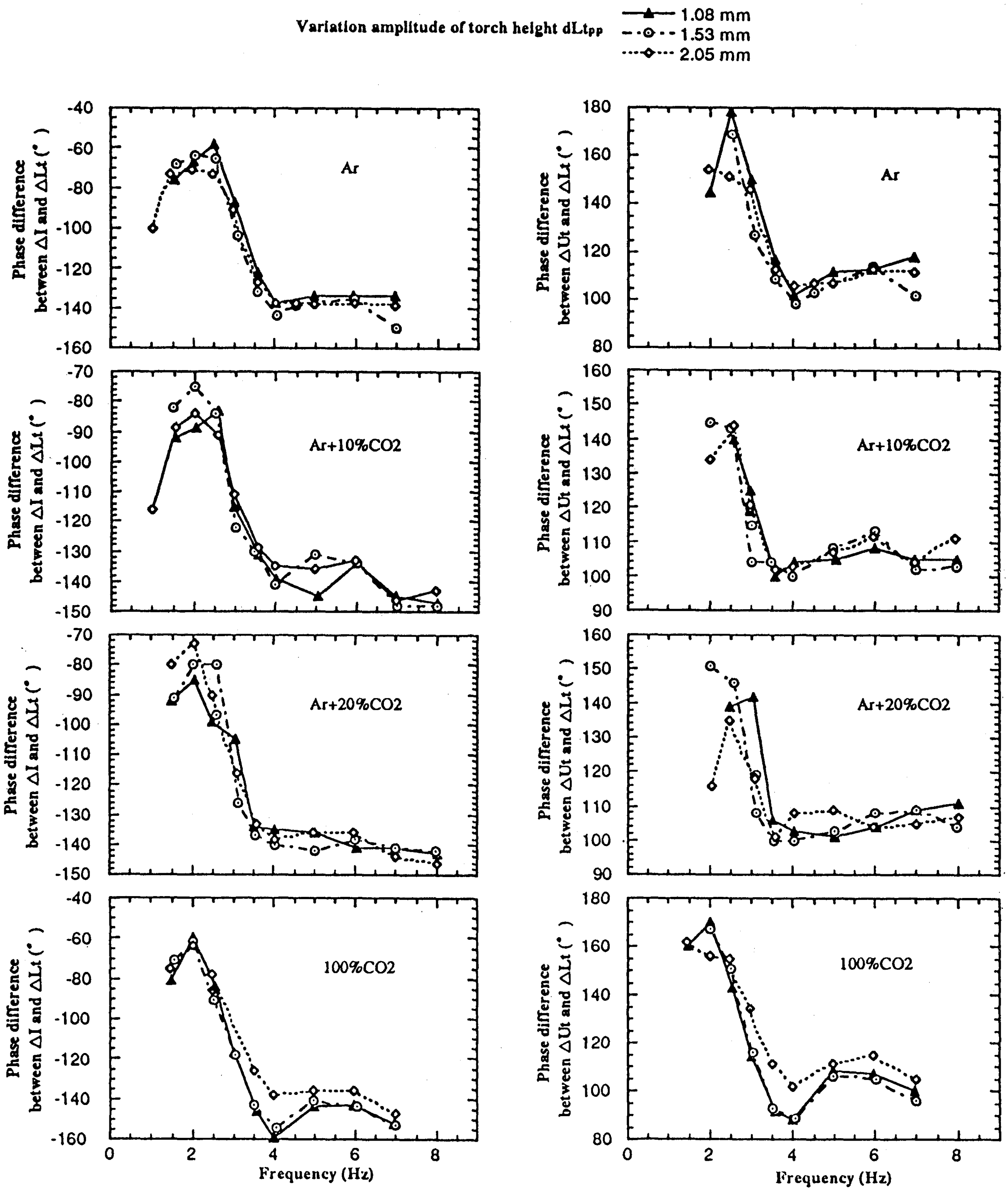


Fig.5 Measured sensitivity-frequency characteristics of the arc sensor in the welding in dip transfer mode



(a) Welding current

(b) Welding voltage

Fig.6 Measured phase-frequency characteristics of the arc sensor in the welding in dip transfer mode may be responsible for the phenomena occurring in the characteristics of the sensor in welding in dip transfer mode.

It is known that the surface tension and the arc pressure acting on a droplet greatly affect the short-circuiting frequency in welding in dip transfer mode. The surface tension of a droplet is predicted to be greater in welding using pure Ar for there are not enough active particles on the droplet surface. Thus, the periods of arc burning and short-circuiting will simultaneously get longer ,i.e., a lower short-circuiting frequency occurs for the droplet which hardly extends during its growth and hardly be broken off during its bridging with the weld pool. On the other hand, the arc pressure is predicted to be greater in welding using CO_2 since the arc column is forced to shrink so as to provide greater heat to maintain the same current passing through it, and this will also result in longer periods of arc burning and short-circuiting, i.e. a lower short-circuiting frequency.

As is well known, the welding current increases during short-circuiting and decreases during arc burning. Therefore, more intensive variations occur in the welding current during welding with pure Ar and CO_2.

4.2 Approximate analysis

On the basis of the above inferences, the sensitivities of an arc sensor in welding in dip transfer mode should decrease with increasing short-circuiting frequency. The analyses made in this section aims to find a theoretical support of the inference.

Previously, a mathematical model of the arc sensor has been developed by the authors, but it relate to an open arc welding process. The model may be used directly in the arc burning duration in an approximate sense. However, 3 things should be accounted for the model if it is also to be used in the short-circuiting period:

(1) The arc voltage is equal to zero,

(2) The melting rate of the electrode is near to zero,

(3) The change of the droplet resistance during a short-circuiting period should be included in the electrode resistance.

According to above considerations, an approximation for welding in the dip transfer mode is proposed as follows:

$$L_a = L_t - L_e$$

$$U_a = u_{ao} + R_a I + E_a L_a$$

$$U_t = U_a + R_e I$$

$$L_w \frac{dI}{dt} + (K_s + R_c)I + U_t = U_s$$

$$\frac{dL_e}{dt} = V_f - \frac{AI}{1 - BJ_e}$$

$$J_e = \int_{t-L_e/V_f}^{t} I^2(\tau)d\tau$$

$$R_e = \int_0^{L_e} r(J_z)dZ$$

$$f_{sc} = f_{save} - K_f(L_a - L_{aave})$$

But, during the short-circuiting period,

$$U_a = 0$$

$$\frac{dL_e}{dt} = V_f$$

$$R_e = \int_0^{L_e} r(J_z)dZ + Rd\left(\frac{t}{T_{sc}}\right)^3 \qquad (0 \le t \le T_{sc})$$

Where

A:	Coefficient in wire melting model (mm A^{-1} s^{-1})
B:	Coefficient in wire melting model (A^{-2} s^{-1})
Ea:	Electric field intensity in arc column (V/mm)
fsave:	Average arc short-circuiting frequency (Hz)
fsc:	Arc short-circuiting frequency (=1/(T_a+T_{sc})) (Hz)
I:	Welding current (A)
Je:	Joule heating weight held at the wire tip (A^2S)
Jz:	Joule heating weight held at the location Z on the wire extension (A^2s)
Ks:	Equivalent output electric resistance (slope of the U-I characteristic) of power supply at the equilibrium point (V/I)
Kf:	The change rate of short circuiting frequency due to arc length variation
La:	Arc length (mm)
Laave:	Average an length (mm)
Le:	Wire extension length (mm)
Lt:	Torch height (mm)
Lw:	Inductance of welding loop (=L_c+L_s) (H)
Ra:	Electric resistance of arc column (Ω)
Rc:	Resistance of cable (Ω)
Re:	Resistance of wire extension (Ω)
r:	Resistance per unit length of wire extension (Ω/mm)
Ta:	Arcing interval in short-circuiting welding process (s)
Tsc:	Short-circuiting interval in short-circuiting welding
Ua:	Arc voltage (V)
uao:	Constant component in arc voltage model (V)
Us:	Equivalent output voltage of welding power source in the state of I=0 (Equivalent electro-motive force)
Ut:	Welding voltage (=U_a+U_e) (V)
Vf:	Wire feeding rate (mm/s)

Basic values of the parameters in the model used in simulation are shown in **Table 2** if no mentioned separately.

Figure 7 shows an example of the real time wave forms produced by the above model. It is seen that the predicted results are similar to the experimental results in Fig. 2. As for the experimental measurements, the values of sensitivities and phase differences of the arc sensor in simulation are calculated after having determined amplitudes and phases at a fundamental frequency by means of DFT to process the wave forms produced by the model in Fig. 7. Calculated results are summarized in **Fig. 8** where Figs. (a) and (b) represent the sensitivity and phase characteristics of current and voltage respectively of the arc sensor. In these calculations, the average short-circuiting frequency f_{save} and short circuiting period T_{sc} are kept constant as 60 Hz and 0.25 ms.

Comparing these with the experimental results shown in Figs. 5 and 6, it can be noticed that there is a good similarity between them concerning the effect of torch height variation frequency on the characteristics. The predicted results show that a greater value for K_f tends to increase the sensitivities of the sensor, especially in the frequency range greater than 4 Hz, but almost no effect appears on the phase-frequency characteristic. The predicted results of the effect of f_{save} on the frequency characteristics of the arc sensor are shown in **Fig. 9** where K_f is assumed to be 10 Hz/mm and f_{save} is respectively set at 40 Hz, 60 Hz, 100 Hz and infinitely greater, i.e., DC welding. The short-circuiting periods corresponding to them are respectively assumed as 0.35 ms, 0.25 ms, 0. 1 ms and 0 ms. The calculated results show that the sensitivities of the arc sensor increase with a decrease of short-circuiting frequency, so it is clear that the change trends of the sensitivity characteristic are also very similar to the experimental results, and the inference previously mentioned is confirmed by these approximate simulations.

Table 2 Fundamental values of the parameters in arc sensor's model used in simulations

$I_o = 200$ A	$R_c = 0.004\,\Omega$
$V_f = 86.8$ mm/s	$u_{ao} = 10$ V
$L_{to} = 20.0$ mm	$R_a = 25$ mΩ
$L_{eo} = 17.1$ mm	$E_a = 0.7$ V / mm
$U_s = 19.7$ V	$A = 0.22 A^{-1}s^{-1}$
$K_s = 0.002$ V/ A	$B = 6.27\times10^{-5} A^{-2}s^{-1}$
$L_w = 0.3$ mH	$K_f = 10$ Hz/mm
$R_d = 25$ mΩ	$f_{save} = 60$ Hz
$T_{sc} = 0.25$ ms	

In order to obtain a good precision of quantitative predicted results, the model obviously should be improved. At least, the effort to establish exact models concerning the growth and the transfer of a droplet to weld pool in a dynamic state is justified.

4.3 SN ratio

SN(Signal vs. Noise) ratio is a dominant factor governing the successful application of the arc sensor. As previously mentioned, the SN ratio in the case using the welding current as detected signal is much higher than that using the welding voltage. In general, the increase of the sensitivity of a sensor is good an improvement of its SN ratio. However, this is not always the case for an arc sensor in welding in dip transfer mode. **Figure 10** expresses an example of the case, where Figs. 10 (a) and (b) express the current-torch height characteristic when welding using pure Ar and Ar+10%CO_2 respectively. It is obvious that the SN ratio at the case of 3 Hz variation of the torch height is much higher than that in the case of 6 Hz, although the sensitivities of current in both cases are very near in value. This phenomenon may be also due to the short-circuiting of droplets. With the variation frequency of the torch height becoming larger the frequency of the fundamental component will come near to the frequency of the main short-circuiting, so it becomes more and more difficult to remove the influence of the short-circuiting on the fundamental component signal if a low pass filter is used for data processing.

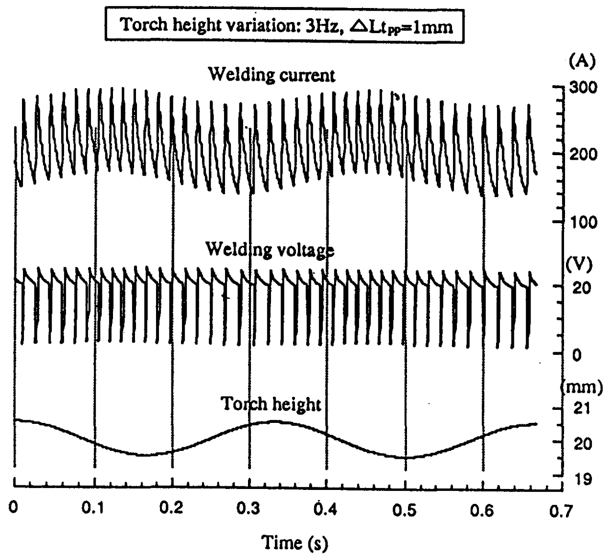
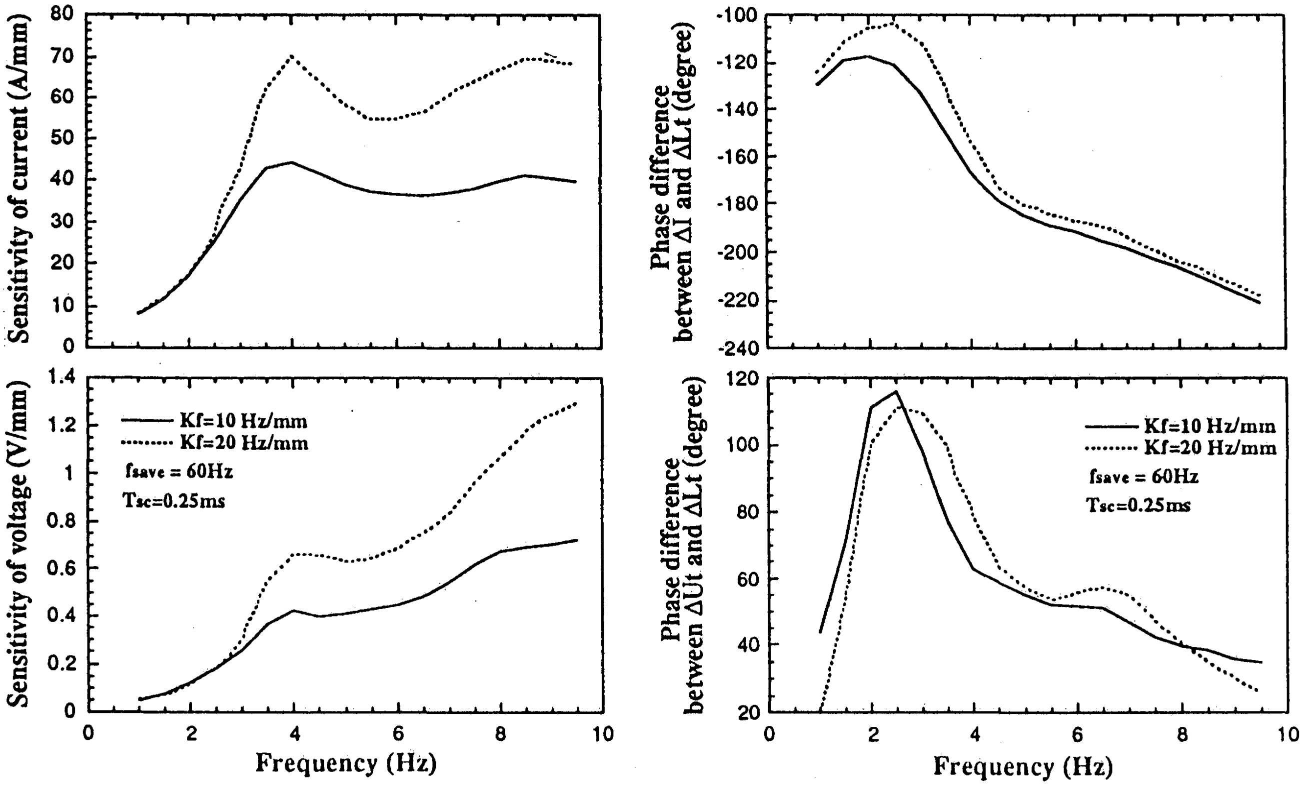


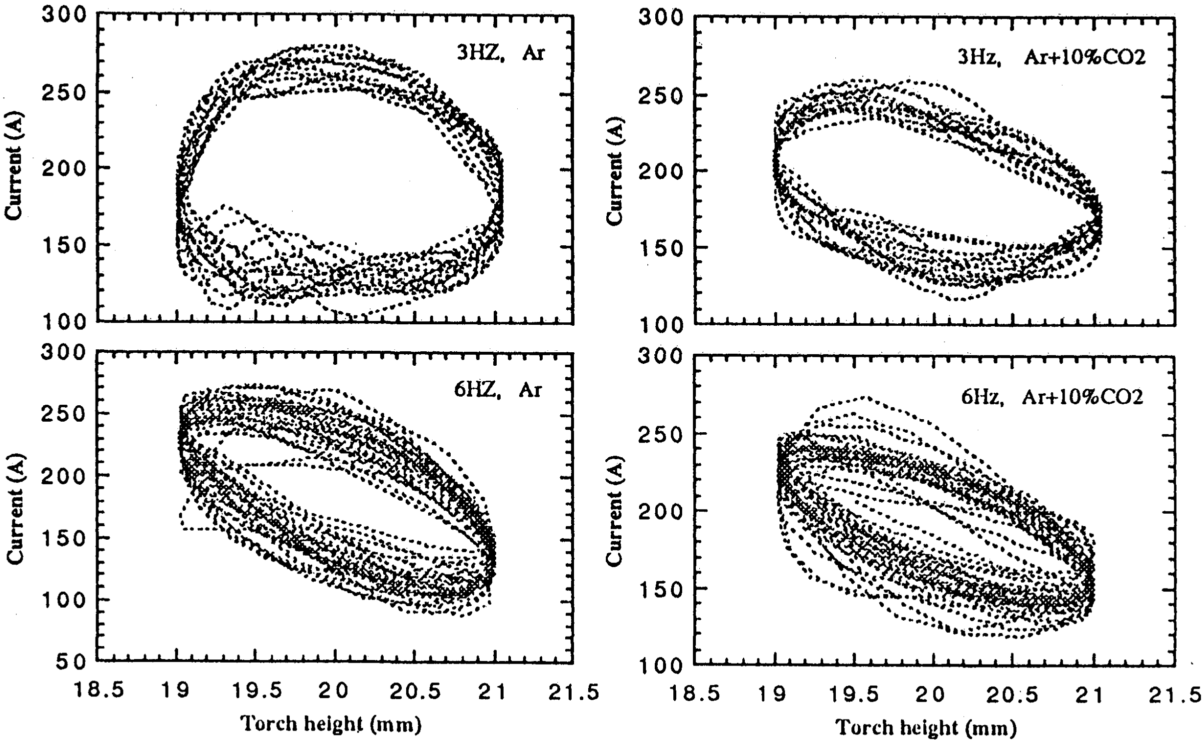
Fig.7 An example of real time wave forms generared by simulation based on arc sensor's model



(a) Sensitivity characteristic

(b) Phase characteristic

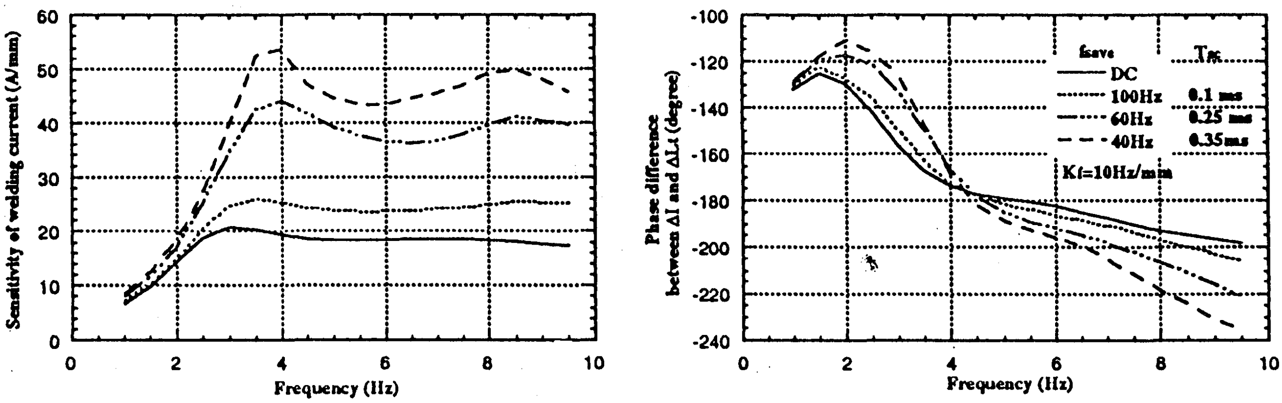
Fig.8 Predicted frequency characteristics of the arc sensor in the welding in dip transfer mode and effect of Kf



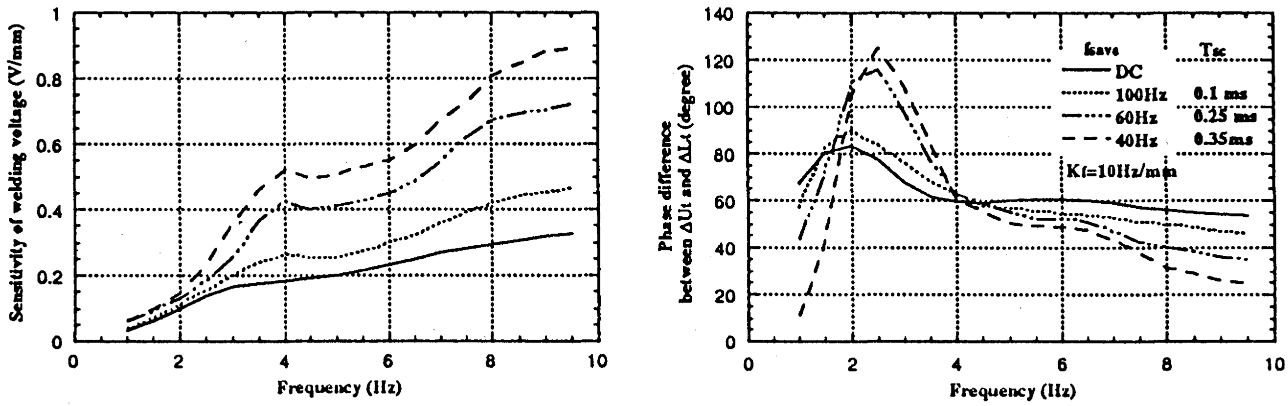
(a) Ar

(b) Ar+10%CO2

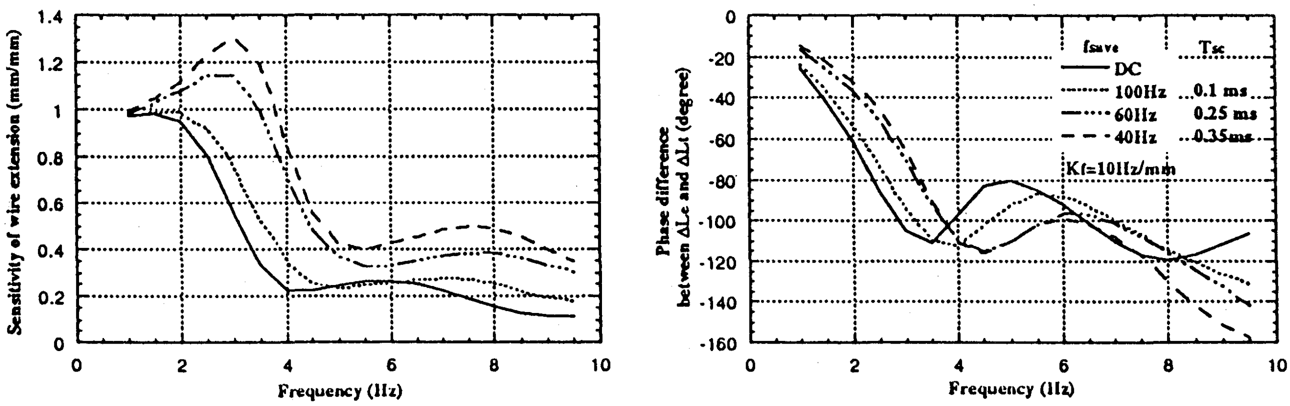
Fig.10 Effects of shielding gases and variation frequencies on the SN ratio of the arc sensor in the welding in dip transfer mode



(a) Welding current response



(b) Welding voltage response



(c) Wire extension response

Fig.9 Predicted effect of fsave on the frequency characteristics of the arc sensor in the welding in dip transfer mode

That the results shown in Figs. 5 and 6 are available with a relatively before precision should be contributed to a huge numbers of data acquisition which in general contains about 15 cycles of fundamental wave forms for obtaining one experimental data. However, in real applications of the arc sensor, recognition should be based on the data of only one cycle. This may be a large problem which impedes the successful application of the arc sensor in welding in dip transfer mode in practice.

5. Conclusions

(1) Compared with welding in spray transfer mode, the sensitivities of the arc sensor in the welding in dip transfer mode are much higher. This phenomenon occurs due to the short-circuiting of droplets, and the higher the short-circuiting frequency, the lower the sensitivities of the arc sensor becomes.

(2) The effect of shielding gas on the sensor in the welding in dip transfer mode also differs from that in the welding in spray transfer mode. The arc sensor in pure Ar arc welding displays the highest sensitivitiy composed with mixed gases of Ar and CO_2. To use a shielding gas capable of reducing short-circuiting frequency is normally good for increasing the arc sensor's sensitivity.

(3) The variation amplitude of the torch height almost has no effect, but its variation frequency has a great effect on the sensitivity of the arc sensor. An arc sensor's current sensitivity generally increases with increasing frequency and reaches its peak level at about 3~3.5 Hz. Then it decreases slightly with increasing frequency but again increases beyond about 5 Hz. An arc sensor's voltage sensitivity in general increases with increasing frequency but it slightly decreases or remains constant in the 1~2 Hz frequency range centered at about 4 Hz.

(4) The SN ratio of the arc sensor's current is much better than that of its voltage signal. Concerning the SN ratio of the current signal, it seems to be the best at about 3 Hz of the torch height variation.

(5) The variation phase of the arc sensors current delays, but its voltage phase advances compared with that of the torch height. The current's phase delay and the voltage's phase advantage are all less than 180 degree according to our experiments. Moreover, the effect of torch height variation frequency on the changes of the current's phase delay and the voltage's phase advance mainly appears in the frequency range less than about 4 Hz. In the range exceeding 4 Hz, the current's phase delay and the voltage's phase advance keep almost constant.

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