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PHASE STABILITY OF THE NEW LOCAL OSCILLATOR SYSTEM FOR THE λ 8-CM RADIOHELIOGRAPH AT TOYOKAWA

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Abstract

Phase stability of the new local oscillator system for the λ 8-cm radioheliograph at Toyokawa is studied experimentally. The phase stability is expected to be kept within 5° rms for a month, if the temperature, DC supply voltage and reference-signal level of a phase-locked oscillator are controlled suitably, and coaxial cables transmitting the reference-signal are burried at the depth below 1 m from the ground level.

1. Introduction

The λ 8-cm radioheliograph at Toyokawa is a T-shaped array of 3-m φ dishes and consists of (32+2) elements in the E-W direction and of (16+1) elements in the N-S direction. (Ishiguro et al., 1975). At present, radio waves received by each antenna in the radioheliograph are directly transmitted, before the amplification and the frequency conversion, to a remote front-end receiver at the phase center of the antenna array through a tournament system of waveguides. When the transmission lines are exposed to the open air, non-uniform thermal expansion is brought about, which results in a phase error. The phase error sometimes increases as high as 20° rms. In order to keep the solar map of good quality, the phase error is desired to be suppressed less than 5° rms. In addition, the transmission loss amounts to 4 dB and causes a serious reduction in sensitivity.

In 1978, we initiated a project (Ishiguro et al., 1979) to improve the phase stability and the sensitivity of the system by replacing the waveguides with 51 sets of low-noise, phase stable front-end receivers and low-loss, phase stable coaxial cables. The design goal of the overall phase stability of the system is 5° rms. Fig. 1 shows the new front-end receiver system. The observing frequency is 3748.5 MHz. A phase-locked oscillator (PLO) generates the first local signal (3540.5 MHz) locked to a reference-signal which is transmitted through a coaxial cable from a master oscillator. Tha coaxial cable which has small temperature coefficient of electrical length is chosen, and is to be burried under the ground to minimize the effect of temperature variation. Since the phase errors originated in a RF amplifier and a mixer are considered to be small, the phase stability of the first local signal dominates the total phase characteristics of the new system. Therefore, the phase stabilities of the coaxial cable and of the PLO are studied experimentally.

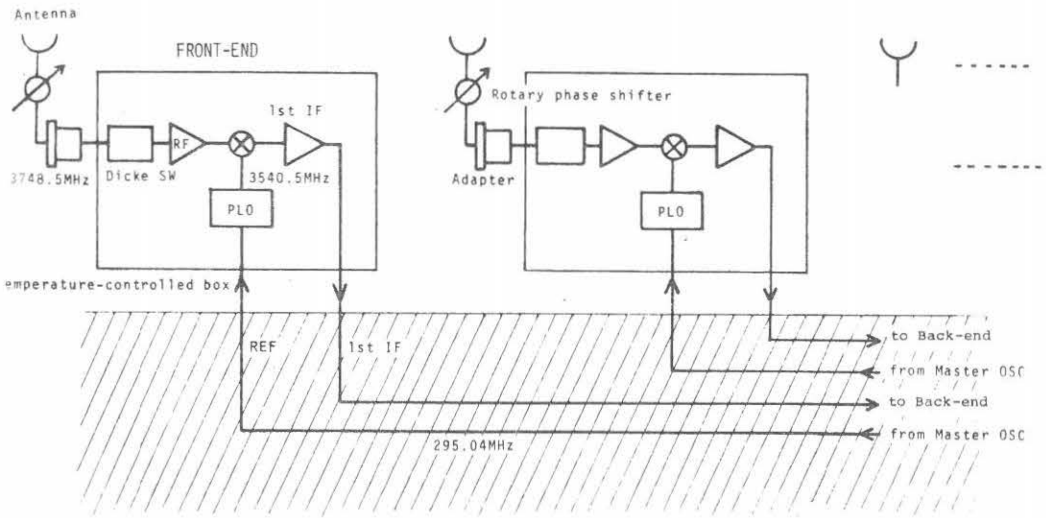


Fig. 1. The new front-end receiver system

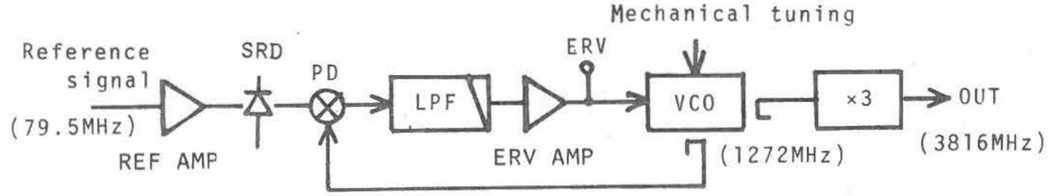
In this paper, various effects on the phase stability of the PLO are carefully examined. The results of the measurement of the temperature coefficient of the coaxial cable, and the requirements on the design of the temperature-controlled front-end box are also described.

2. Phase stability of the PLO

2. 1 Measurement of the Phase Stability of the PLO

We used PLO's which are on the market. (Nihon Tsushinki Co., Ltd. model 3852B). A block diagram of the PLO is shown in Fig. 2. In this PLO, the (input) reference-signal is amplified, and harmonics of the amplified signal are generated by the step-recovery diode (SRD), then the voltage controlled oscillator (VCO) is locked to one of the harmonics at around 1.3 GHz in the phase-locked loop, and the output frequency of the loop is multiplied by 3. In this experiment, the frequency of 79.5 MHz is used as the reference-signal and the VCO is locked to the 16th harmonics of the reference-signal frequency, and the final frequency is 3816 MHz.

Fig. 3 shows the method of measuring the relative phase between the two PLO's locked to a common reference-signal. A crystal oscillator has a frequency stability of 10^{-8}/day. Each PLO is connected to a



REF AMP: Reference-signal amplifier
SRD : Step-recovery diode
PD : Phase detector
ERV : Error voltage
VCO : Voltage-controlled oscillator

Fig. 2. The block diagram of the PLO.

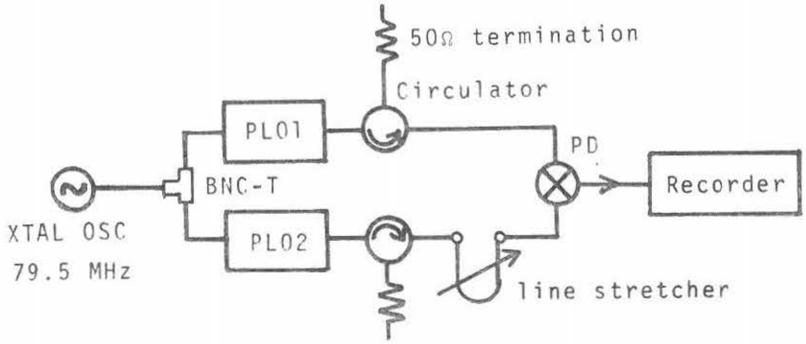


Fig. 3. The method of measuring the relative phase between two PLO's.

phase detector (PD) through a circulator so as to minimize the interference between the PLO's. A double-balanced mixer is used as the PD. A line stretcher is inserted to calibrate the PD or to offset phase in order to use it at the maximum sensitivity. A vector voltmeter (1-1000 MHz) is used to measure the reference-signal level. The temperature of each PLO is measured with an accuracy of 0.1°C.

The relative phase between the PLO's is influenced mainly by the difference in the characteristics of the PLO's against the variations of the ambient temperature, the DC supply voltage and the reference-signal level. The results of the measurement are as follows:

(a) Phase error due to the temperature variation

When the temperature of the two PLO's is changed simultaneously, the temperature coefficient of the relative phase is +9°/°C. To investigate the individual effect on the relative phase, the temperature of one PLO is changed while the other is left unchanged. The result is shown in Fig. 4. The temperature coefficients are +12°/°C and +4°/°C for PLO-1 and PLO-2, respectively. These values are obtained at around 40°C.

(b) Phase error due to the change in DC supply voltage

The variation of the relative phase against the change in DC supply voltage is measured in case that the voltage of the two PLO's are changed altogether and in case that only the voltage of the one PLO is changed, in the same way as in (a). The result is shown in Fig. 5. When the two PLO's are connected to the common power supply, the variation of relative phase is +80°/V. When separate power supplys are

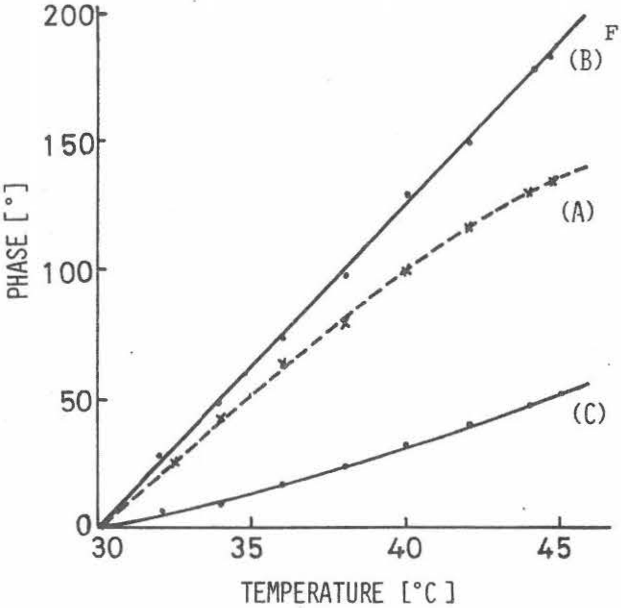


Fig. 4. The phase error due to the temperature variation
(A) When the temperature of the two PLO's are changed altogether,
(B) When only the temperature of the PLO-1 is changed,
(The temperature of the PLO-2 is 40°C.)
(C) When only the temperature of the PLO-2 is changed,
(The temperature of the PLO-1 is 40°C.)

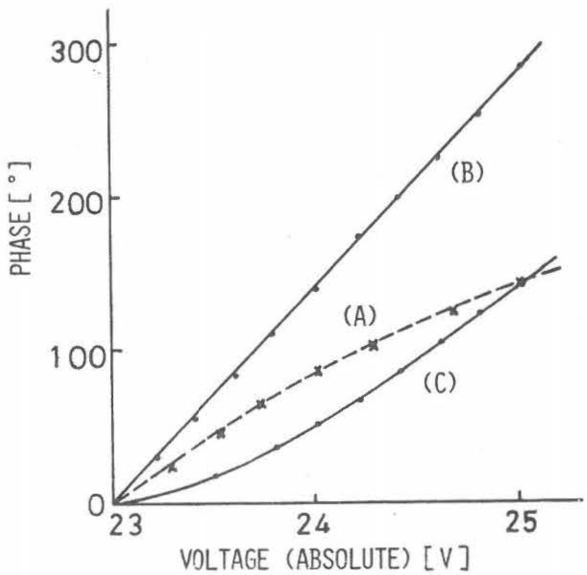


Fig. 5. The phase error due to the change in DC supply voltage.
(A) When the voltage of the two PLO's are changed altogether,
(B) When only the voltage of the PLO-1 is changed,
(The voltage of the PLO-2 is 24.0 V.)
(C) When only the voltage of the PLO-2 is changed,
(The voltage of the PLO-1 is 24.0 V.)

used, the results are +170°/V and +80°/V for PLO-1 and PLO-2, respectively. These values are obtained at around 24.0 V.

(c) Phase error due to the change in the reference-signal level

The change in the reference-signal level causes a phase variation of 1.2°/mV at around the level of 470 mV. The characteristic is shown in Fig. 6.

It is clear from (a) and (b) that the total characteristic is consistent with the separate experiments.

2. 2 Analysis of the Phase Instability

It is desirable to know which part of the PLO dominates the phase instability. First, the individual effects of DC voltages for the reference-signal amplifier (REF AMP), the VCO and the error signal amplifier (ERV AMP) are investigated. The results are shown in Fig. 7. It is seen that the REF AMP has dominant effect on the phase error resulted from the change in DC supply voltage.

The temperature characteristics are reexamined, when circuit boards which include the REF AMP, the SRD and the PD are interchanged between the two PLO's. It turns out that the temperature characteristics are almost reversed. Therefore, it can be said that the REF AMP, the SRD and the PD have dominant effect on the temperature characteristic of the phase error.

If f [MHz] and f_i [MHz] are the free running frequency of the VCO and the frequency of the reference-signal, respectively, the steady-state phase error θ [rad] is expressed as follows;

$$\theta(f) = \frac{2\pi(f-f_i)}{A\ K} ,$$

where K [MHz/V] is a constant corresponds to the sensitivity of the VCO to the error voltage and A [V] is a constant which is determined by the gains of the PD, the low pass filter (LPF) and the ERV AMP. So, assuming that when f changes into $f+f_e$, θ changes into $\theta+\theta_e$,

$$\theta_e = \frac{2\pi f_e}{A\ K} = \frac{2\ \pi}{A} V_e , \qquad \text{where } V_e = \frac{f_e}{K} ,$$

then, $$A = \frac{2\pi}{\theta_e} V_e .$$

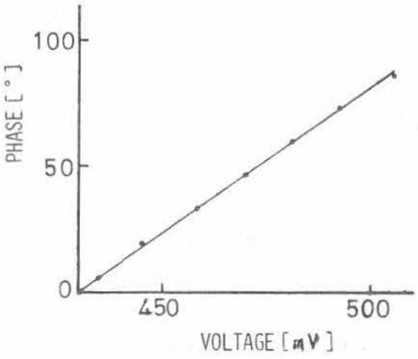


Fig. 6. The phase error due to the change in the reference-signal level.

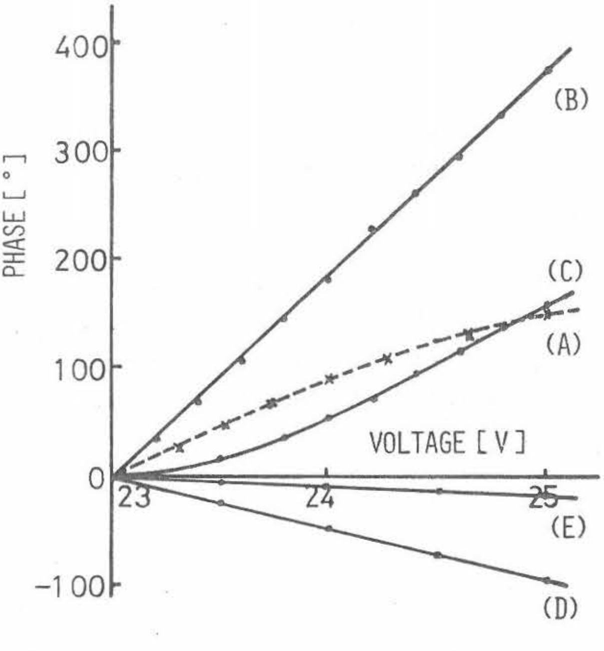


Fig. 7. The individual effects of DC voltage for the REF AMP, the VCO and the ERV AMP.

(A) When the voltage of the two PLO's are changed altogether,

(B) When only the voltage of the REF AMP of the PLO-1 is changed,

(C) When only the voltage of the REF AMP of the PLO-2 is changed,

(D) When only the voltage of the VCO and the ERV AMP of the PLO-1 is changed,

(E) When only the voltage of the VCO and the ERV AMP of the PLO-2 is changed.

The constants K and A are measured by changing f mechanically. The two PLO's have almost the same values of K, 0.7 MHz/V. On the other hand, values of A are 13 V and 60 V for PLO-1 and PLO-2, respectively. The loop gains of the phase-locked loop are different for the two PLO's. This will be one of the reason for the difference in phase characteristics of the two PLO's.

From the experimental results mentioned above, it is made clear that the phase instability in the REF AMP is predominant, and the number of multiplication at the SRD is the important factor to the phase error. Therefore, if the number of the multiplication is reduced by using a higher reference-signal frequency, the phase stability will be improved.

3. Estimate of the stability of the electrical length of a coaxial cable burried under the ground

In transmitting a reference-signal, phase error is caused by the change of electrical length of the coaxial cable due to the temperature variation. The variation of the electrical length due to the temperature variation is examined. A foamed-polyethylene coaxial cable of 150 m in length, 80 % foaming rate, 50 Ω, 9.5 mm in diameter was chosen as the test cable. The phase difference between the input port and the output port of the cable is measured by the vector voltmeter as shown in Fig. 8. Fig. 9 shows the result of the measurement. The temperature coefficient is about 6×10^{-6}/°C. The deviation of the temperature coefficient is estimated to be $(6\pm1.5)\times10^{-6}$/°C.

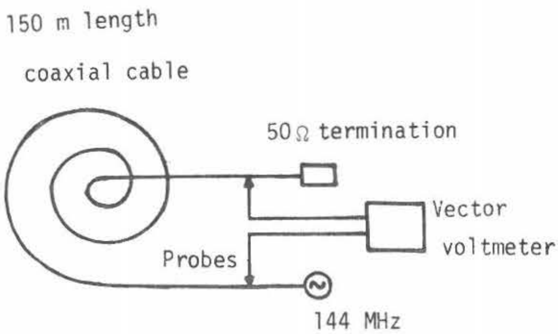


Fig. 8. The method of measuring the stability of the electrical length of a coaxial cable.

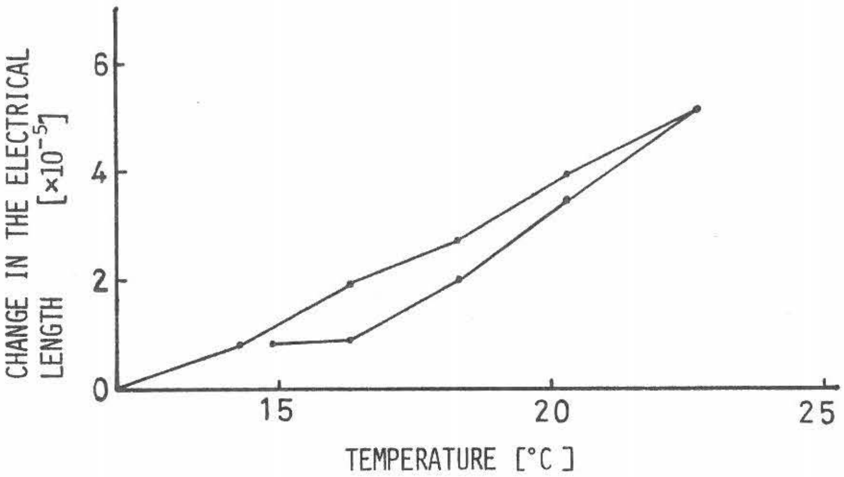


Fig. 9. The variation of the electrical length of the foamed-polyethylene coaxial cable due to the temperature variation. A temperature sensor is set among the muti-looped cable. A hysteresis phenomenon is seen, which means the temperature around the sensor is delayed to the average temperature of the whole cable.

As the temperature coefficient of the dielectric constant of the polyethylene is negative and surpasses the positive coefficient due to thermal expansion, the temperature coefficient of the electrical length of usual coaxial cables is negative. In foamed-polyethylene coaxial cable, the effective dielectric constant can be made so small as to equalize a thermal expansion.

Underground temperature is measured at the depth of 0.5 m, 1 m and 2 m, from May 25 1978 to Feb. 28 1979. The sensing circuits are calibrated by a precise thermometer. Deviation from calibration curve is 0.1°C rms. Temperature variation during a few days in November 1978 is shown in Fig. 10. Daily variation can be clearly seen for the record at the depth of 0.5 m, but it can not be recognized for that at the depth of 1 m. Yearly variation of the temperature is estimated as less than 0.1°C/day at the depth below 1 m.

If a coaxial cable which has the temperature coefficient of 6×10^{-6}/°C is burried at the depth below 1 m, the variation of the electrical length due to the temperature variation is expected to be kept within 6×10^{-7}/day.

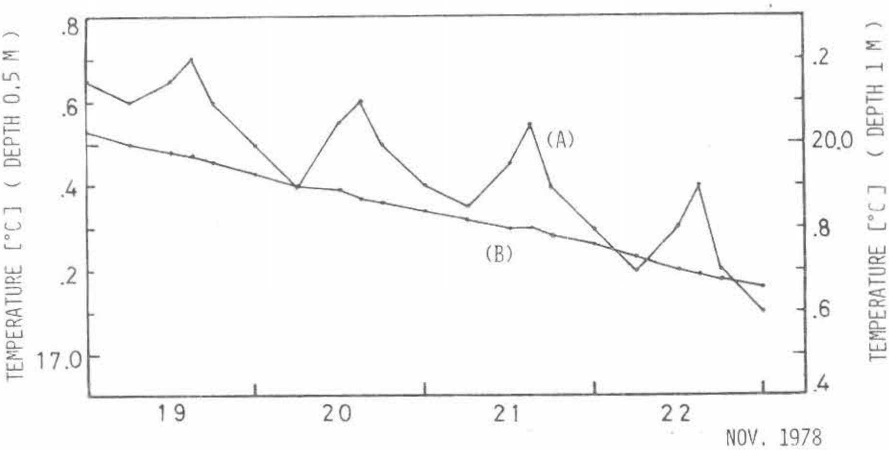


Fig. 10. The underground temperature during four days in November 1978.
(A) The underground temperature at the depth of 0.5 m.
(B) The underground temperature at the depth of 1 m.

4. Summary

Phase stabilities of the PLO generating the first local signal and of the coaxial cable transmitting the reference-signal are studied experimentally.

The phase stabilities of the PLO against the change in the ambient temperature, the DC supply voltage, and the reference-signal level, are shown in Table 1. It is not so difficult to keep the DC supply voltage and the reference-signal level within the values shown in this Table. It is possible to realize the temperature variation within 0.1°C rms by using a temperature-controlled box as described in Appendix.

It is made clear that the phase instability in a multiplication stage is predominant for the total phase stability, therefore it is better to use a higher frequency as a reference-signal, and that it will be possible to improve the relative phase stability of the PLO's by minimizing the difference in the electrical characteristics (such as loop gain) of the phase-locked loop as far as possible.

Parameter	Parameter stability	Phase stability
Temperature	0.1°C rms	0.9° rms
DC supply voltage	10 mV rms	0.8° rms
REF signal voltage	0.5% rms	2.8° rms

Table 1. Parameters which effect the phase stability of the PLO.

The temperature coefficient of the electrical length of the foamed-polyethylene coaxial cable is about $6\times10^{-6}/°C$. If the coaxial cable of 120 m long is burried at the depth below 1 m from the ground level, the phase stability is expected to be kept within 0.2°/day at the first local signal frequency of 3540.5 MHz.

If the variation of each parameter is considered as a random variable, and the variations are independent each other, total phase stability is expressed in RSS (root sum square). The total phase stability of the new system is expected to be kept within 5° for a month, if the coaxial cables are burried at the depth below 1 m from the ground level.

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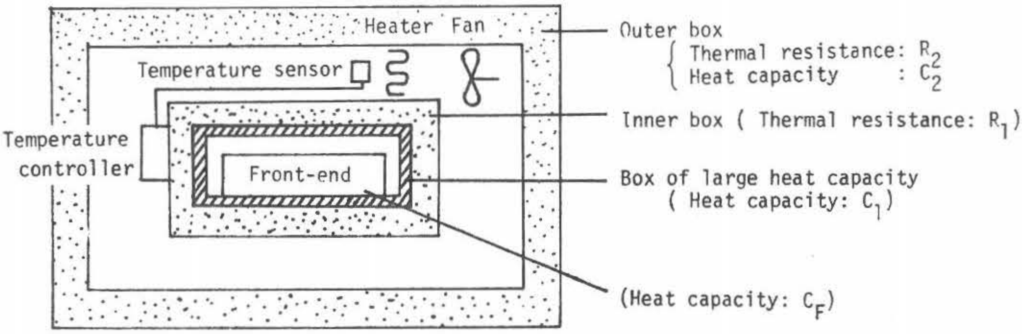
Appendix

A design of a temperature controlled front-end box

Temperature variation of the PLO must be kept within 0.1°C rms from the preceding discussion. We describe about the front-end box which controls the temperature of the front-end within $\phi_c \pm 0.15$°C, where ϕ_c is a certain constant temperature. The range of atmospheric temperature variation is assumed to be from -5°C to 37°C. As the magnitude of ϕ_c scarcely affects the performance of the front-end at around usual temperature, the front-end box is not necessarily cooled. Also, ϕ_c needs not to be changed all the year round. We assumed that the temperature rise θ_F [°C] due to the power consumption of the front-end (10 W) is 7°C, and that the margin for the assumed maximum atmosheric temperature (37°C) is 2°C. So, 46°C is adopted as ϕ_C. The front-end box has double structure as shown in Fig. 11. The air temperature in the outer box is controlled, and the residual temperature variation is smoothed by the inner box.

If R_1 [°C/W] and R_2 [°C/W] are thermal resistance of the inner box and the outer box, respectively, R_1+R_2 is calculated to be 0.7 °C/W. Thermal resistance of the air is negligible at the steady-state. Assuming that R_2 is 0.5 °C/W, average power of 88 W is required for a heater at the assumed minimum atmospheric temperature (-5°C).

A temperature-control circuit has a sensitivity of 0.3°C. But, due to the overshoot, the magnitude of which is determined by the delay in detecting the change in temperature and by the maximum power



Note: The value of C_2 includes the heat capacity of the fan, that of the heater and that of the supporters of the inner box, etc.

Fig. 11. An outline of the proposed temperature-controlled front-end box.

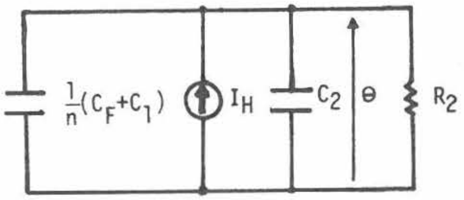


Fig. 12. The equivalent circuit for calculating the period T.

of the heater, the temperature variation around a temperature sensor will be larger than 0.3°C. This delay is determined by the equivalent thermal resistance of the air between the sensor and the heater, the heat capacity of the heater, and the finite response time of the temperature control circuit. As the equivalent thermal resistance of the air changes extremely, according to the wind velocity of a fan, and to the shapes of the sensor and the heater, it is difficult to calculate the exact magnitude of the overshoot.

So, we calculate the period of the air temperature variation T [sec] in the outer box in case that amplitude of the variation is fiven by θ_0, using an equivalent circuit as shown in Fig. 12. θ_0 is obtained by experiment. In this equivalent circuit, C_F [J/°C], C_1 [J/°C] and C_2 [J/°C] are the heat capacities of the front-end, the inner box and the outer box, respectively. Also, I_H [W] is a maximum power of the heater. It is designed that the amplitude of the temperature variation of the front-end is reduced to one n-th part of the amplitude of the air temperature variation in the outer box. If ϕ_A [°C] is atmospheric temperature, the period of the air temperature variation T, is expressed as follows;

$$T = CR_2[\ln\{1+2\theta_0/(\theta_H-\theta_g-2\theta_0)\}+\ln\{1+2\theta_0/\theta_g\}], \qquad (1)(1)$$

where $C = \frac{1}{n}(C_F+C_1)+C_2, \quad \theta_H = I_H R_2, \quad \theta_g = \phi_C-\theta_F-\phi_A,$

$$2°C \leqq \theta_g \leqq 44°C.$$

The air temperature variation in the outer box is approximated by the sine curve which has the amplitude of θ_0 and the period of T. The condition, on which the temperature variation of the front-end is reduced less than θ_0/n at T_{max} by smoothing effect of the inner box, is given by;

$$T_{max} \leqq 2\pi R_1(C_F + C_1)/n. \qquad (2)$$

If T has a maximum at $\theta_g = \theta_{gm}$ in Eq. (1), a following equation is derived from Eqs. (1) and (2),

$$C_F+C_1 \geqq \frac{nC_2R_2A}{2\pi R_1 - R_2A}, \qquad (3)$$

where $A = \ln \dfrac{(\theta_H - \theta_{gm})(\theta_{gm} + 2\theta_0)}{\theta_{gm}(\theta_H - \theta_{gm} - 2\theta_0)}$

It is confirmed experimentally that θ_0 can be made less than 0.4°C in case of I_H = 120 W. Due to the error of the temperature sensor, average value of the air temperature variation will change slowly, but this slow variation cannot be smoothed by the inner box. As the result of the measurement, the variation of the average value is less than 0.1°C. So, if θ_0 is 0.5°C, n = 10 is the necessary condition to control the temperature variation of the front-end within ±0.15°C. We assume θ_H = 55°C. Values for R_1 and R_2 are given as 0.2 °C/W and 0.5 °C/W, respectively. θ_{gm}= 2°C is derived from Eq. (1). Therefore, from Eq. (3),

$$C_F + C_1 \geq 2.0\ C_2\ . \tag{4}$$

Above equation is the necessary condition to meet the requirement of the design specification of the front-end box.