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An active-passive beam current transformer

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Abstract In this article, a new type current transformer was developed using an active-passive circuit to improve low frequency response of the system without impairing high frequency response. The active-passive current transformer with In-flange was fabricated. Theoretical analysis, numerical simulations and experimental results are given.

Key words Beam current transformer, Active-passive circuit, In-flange, Frequency response

CLC number TL506

1 Introduction

Developing linear accelerators requests a wide-band beam current monitor[1-3], in which the rise time is short enough to measure mini-pulses and the descending time constant is large enough to measure macro-pulses. At Spallation Neutron Source (SNS), to obtain the desired accuracy and resolution, pulses of the digitally compensated beam current transformers must be in rise time of <1 ns and droops of 0.1% per ms[1,2]. At CERN, the CLIC (Compact Linear Collider) Test Facility 3 (CTF3) has a wide band Wall Current Monitor (WCM)[3], in which a direct output works in a bandwidth of 250 kHz to 10 GHz, while another uses an active integrator to compensate the residual droop and works in a bandwidth of 10 kHz to 300 MHz.

Generally, the beam current transformer is suitable for measuring macro-pulses with its large descending time constant[4]. Mini-pulses can be measured using a beam current transformer by decreasing the ascending time constant with reduced windings, but this in turn results in decreased descending time constant and affects the macro-pulse measurement[5]. Such a contradiction for measuring both mini- and macro-pulses can be solved by a wide-band beam current monitor.

In this article, we present a current transformer using an active-passive circuit to improve the low frequency response of the system without impairing the high frequency response. And the circuit is simpler than the other methods[1-3].

2 Theoretical analysis

The active-passive circuit of the beam current transformer is shown in Fig.1.

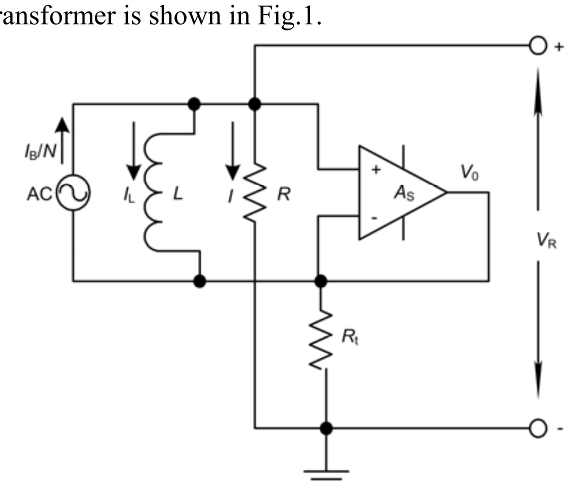

Fig.1 The active-passive circuit to improve low frequency response of the beam current transformer.

Suppose the transfer function of the operational amplifier is

$$A_s = \frac{A}{1+S/S_0} \tag{1}$$

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where A is the high DC voltage gain ($A≈10^6$). As high-frequency response is obtained by allowing s to approach ∞, i.e. $A_s≈0$, the amplifier is virtually not working, hence no effect of the circuit on high-frequency response.

The low-frequency response is quantitatively analyzed as follows.

For the beam current i_B, its Laplace transform is $I_B(s)=L\{i_B\}$. Suppose the beam current transformer has a primary winding of a single turn and the secondary winding of N turns with inductance L. Through analysis of the circuit in Fig.1, an equation combination can be obtained as

$$\begin{cases} V_R(s)=RI(s) \\ I(s)=I_B(s)/N-I_L(s) \\ V_0(s)=A_s LsI_L(s)=A_s[V_R(s)-V_0(s)] \end{cases} \tag{2}$$

Then, the Laplace transform of the voltage across R is given by

$$V_R(s)=\frac{I_B(s)R}{N}\times\frac{s}{s+\frac{R}{(1+A_s)L}}=\frac{I_B(s)R}{N}\times\frac{s}{s+\frac{s_{RL}}{(1+A_s)}} \tag{3}$$

where $s_{RL}=R/L$. And the frequency response of the active-passive current transformer is given by

$$H(s)=\frac{V_R(s)}{I_B(s)R/N}=\frac{s}{s+\frac{s_{RL}}{(1+A_s)}}=\frac{s}{s+\tilde{s}_{RL}} \tag{4}$$

where $\tilde{s}_{RL}=s_{RL}/(1+A_s)$.

Similarly, the frequency response of a general beam current transformer without active-passive circuit is

$$H(s)=\frac{V_R(s)}{I_B(s)R/N}=\frac{s}{s+s_{RL}} \tag{5}$$

Comparing Eq.(4) and Eq.(5), because $A_s>>1$ at the low frequency, i.e. $\tilde{s}_{RL}$ is smaller than s_{RL}, it can be concluded that the extremum-point of the system with an active-passive circuit is smaller than that of the system without the active-passive circuit. In this way, low frequency response of the system is improved.

3 Transformer structure

The active-passive beam current transformer has an In-flange current transformer (Fig.2), in 40 mm thickness and having 10 turns of winding. It was designed according to Bergoz In-flange CT technique[6]. The core is a nanocrystalline-alloy with initial permeability of 20000.

Fig.2 The In-flange current transformer.

Operational amplifier AD847 (A=3500 and f_0=10 kHz), or LF351 (A=130000 and f_0=30 Hz), was chosen to analyze frequency response of the active-passive circuit.

4 Numerical simulations

Numerical simulations were made for low frequency response of the active-passive current transformer. From Eq.(4), frequency response of the active-passive current transformer is

$$H(s)=\frac{s[s+(1+A)s_0]}{s^2+[(1+A)s_0+s_{RL}]s+s_0 s_{RL}} \tag{6}$$

Eq.(6) was applied to the operational amplifiers of AD847 and LF351 for frequency response at N=10 and $s_{RL}=1.56\times10^4$ Hz, and the s_{RL} value was calculated with the descending time constant of nanocrystalline-alloy core obtained in laboratory experiments.

Fig.3 is frequency response of the beam current transformer with and without compensation using the acitve-passive circuit of AD847 (A=3500 and f_0=10 kHz). It can be seen that the two curves differ little from each other at $f>10^5$ Hz. The low frequency cut-offs with and without compensation using the active-passive circuit are 0.7 Hz and 2.48×10^3 Hz, respectively.

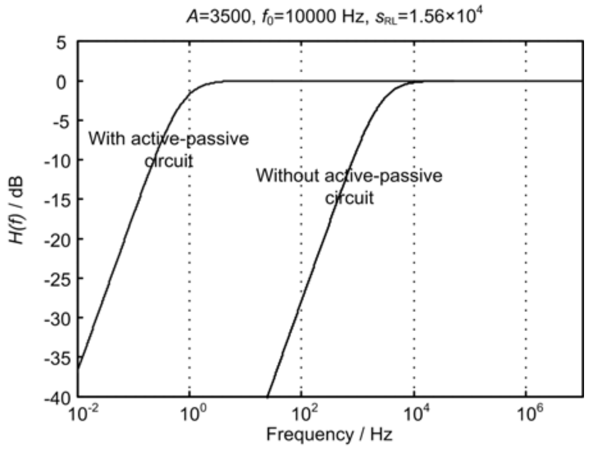

Fig.3 Frequency responses with and without active-passive circuit using AD847 operational amplifier.

Similar result was obtained (Fig.4), from the transformer with and without the acitve-passive circuit of LF351 (A=130000 and f_0=30 Hz), with the low frequency cut-offs at 0.02 Hz and 2.48×10^3 Hz, respectively, for the transformer with and without the active-passive circuit.

The calculations show that it is feasible to use an active-passive circuit to improve low frequency response of the beam current transformer without impairing high frequency response.

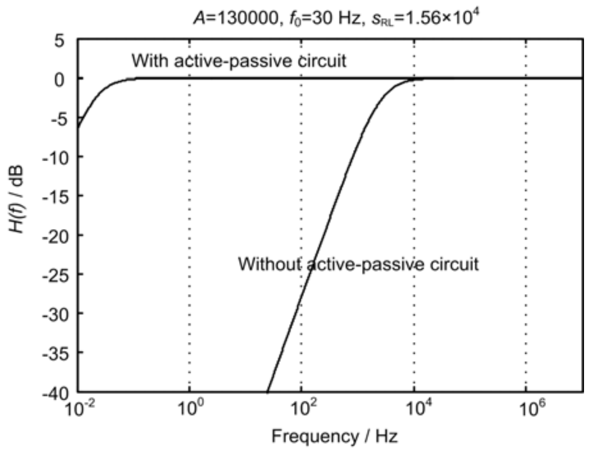

Fig.4 Frequency responses with and without active-passive circuit using LF351 operational amplifier.

5 Results of experimental simulation

The active-passive beam current transformer was tested in experiments, with a signal generator (HP33120) to simulate the beam current and a 500 MHz real-time oscilloscope (TDS3504B) to display the pulses. We restricted our attention to the response with macro-pulses.

The test system is shown schematically in Fig.5. Output waveforms from the transformer with and without the active-passive circuit was checked with 80 mA of simulated beam current on the 50 Ω resistor in pulse widths adjustable from 200 ns to 200 μs. The first channel of the oscilloscope displayed the output waveforms, and the second channel displayed the input voltage waveform.

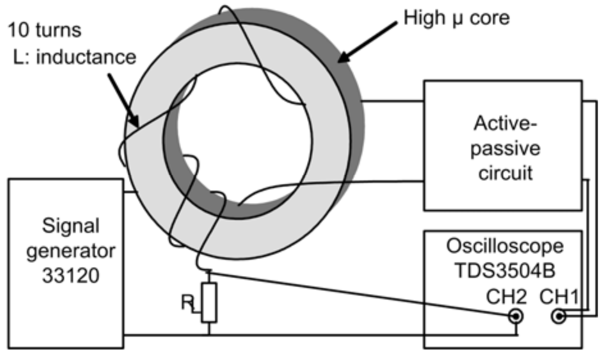

Fig.5 Block diagram of wide-band beam current monitor testing system.

From the output waveforms without the active-passive circuit with 1 ms input pulse (Fig.6), the descending time constant τ is 64 μs. And from output waveforms of the active-passive circuit using AD847 (Fig.7) or LF351 (Fig.8) with 1 ms input pulse, the descending time constants τ are 28 ms and 38 ms, respectively.

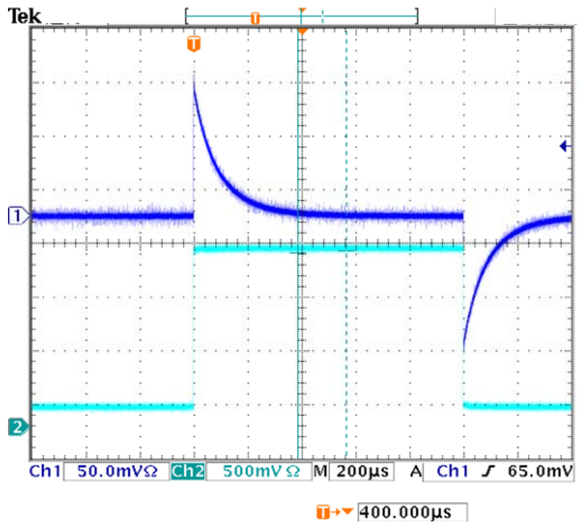

Fig.6 Output waveforms without the active-passive circuit with 1 ms input pulse.

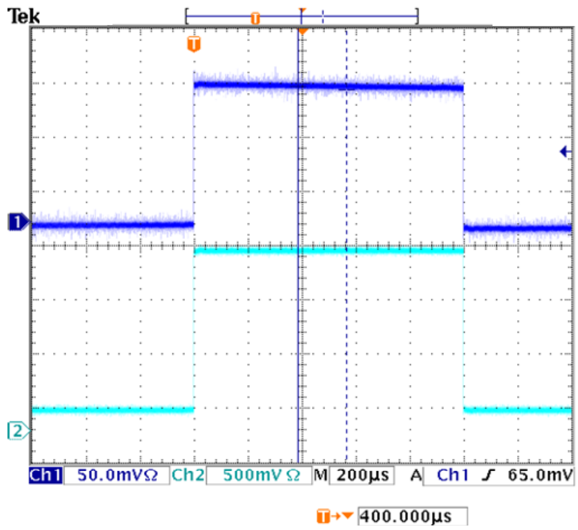

Fig.7 Output waveforms of the active-passive circuit using AD847 with 1 ms input pulse.

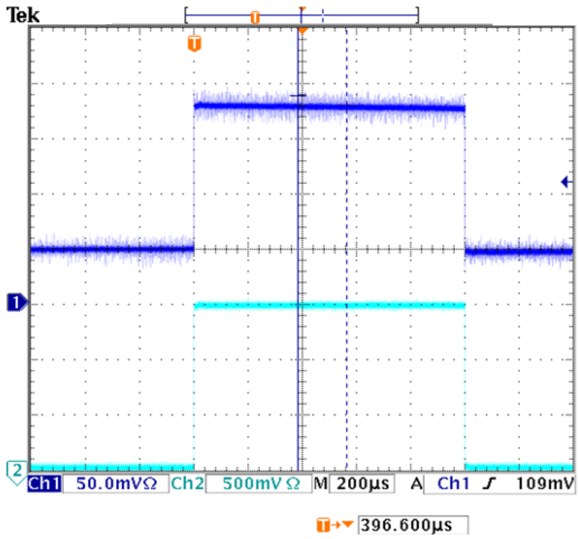

Fig.8 Output waveforms of the active-passive circuit using LF351 with 1 ms input pulse.

From the results, significant improvement was achieved in measuring macro-pulses using the active-passive circuit of AD847 or LF351 operational amplifier, with the latter providing more compensation of transformer droop. This is consistent with numerical simulations for low frequency response of the active-passive current transformer.

6 Conclusion

A wide-band beam current monitor was developed using an active-passive circuit to improve low frequency response of the system without impairing the high frequency response. Theoretical analysis and experimental simulations indicated that LF351 operational amplifier provides more compensation of transformer droop than AD847 operational amplifier. The active-passive circuit can be used in the wall current transformer to improve its low frequency response.

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