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Comprehensive study of Howland circuit with non-ideal components to design high performance current pumps

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ABSTRACT

Howland circuit is a popular high performance, voltage-controlled current pump, which can both sink and source precise amounts of current and provide high output impedance as well as high frequency bandwidth. In this article, analytical expressions are derived for performance characteristics of non-ideal Howland Current Pump, and it is shown that the main characteristics can be adjusted using three independent parameters: resistors' scale, feedback ratio, and current sensing resistor's value. The derived expressions are evaluated by computer simulations, and then are used to design a current pump for an impedance cardiography system, as an example. Performance of the circuit is evaluated based on simulations and experimental tests, and then is compared with several previous designs in the literature. The relationships provide a unified framework for the analysis of different configurations of Howland current pump and can facilitate its design process for different applications with specific performance requirements.

1. Introduction

Electrical current pumps are used in various instruments including those for medical applications to deliver a controllable amount of current to the load (tissue) [1–4]. Two main applications are neural stimulators [1,5–9] and bio-impedance measurement systems. The latter includes electrical impedance tomography (EIT) systems [10–13], impedance cardiography (ICG) [14–16], and bio-impedance spectroscopy systems (BIS) [17,18]. In these applications, a highly stable, usually high frequency current is injected into the tissue to record accurate measurements of the impedance [2,10].

Different circuit topologies implementing current sources have been suggested to be used in these systems [13,19–27]. A common problem in the current pumps is that their performance, especially the output impedance, degrades significantly in high frequencies due to unintended capacitors in active elements. Howland circuit [28] is extensively used to design current pumps [11,12,29–32] due to its bidirectional output, ultra high output impedance as high as several mega ohms at the working frequency [11,30], stable output response over a wide frequency bandwidth as high as several mega Hertz [30,33], as well as the ability to generate arbitrary current waveforms. Some studies have investigated the characteristics and performance of Howland current pump (HCP) in its different configurations. The sensitivity to the tolerance of resistors has been studied for the standard, known also as "modified", configuration of HCP (Fig. 1) [34,35]. Pouliquen et al. [5] have studied the effect of input bias current, offset voltage, slew rate, and output swing of the op-amp on performance of "basic" HCP (See Section 3.1 for the definition). Hammod et al. [36] presented a noise analysis of basic and standard HCP circuits and demonstrated superior temperature stability of the standard configuration. Moreover, the output impedance and the stability at high

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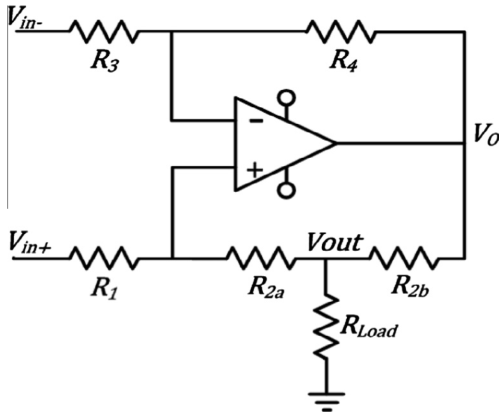

Fig. 1. Schematic of the standard form of Howland current pump.

frequencies have been compared for different configurations of HCP [32,37].

A Generalized Impedance Converter (GIC) can be added at the output of HCP to cancel the parasitic capacitances, hence improving the output impedance of the pump [38]. Wang et al. [39] have demonstrated that the GIC can only cancel the parasitic capacitances in a small limited frequency band, while it degrades the stability of the circuit, and makes the output current vary with the frequency.

Tucker et al. [30] determined the minimum op-amp requirements for a specified precision of HCP. They analyzed the noise and compliance of the circuit, and suggested effective compensation strategies to achieve stability without sacrificing high output impedance. However, their work was limited only to the standard form of the HCP. Liu et al. [31] have performed simulations and experiments to demonstrate the higher performance of a so called "differential" configuration of HCP in comparison to the standard configuration in terms of output impedance, SNR and compliance. These benefits are obtained by floating the load. This is not applicable in some applications when the load must be grounded for safety.

The analyses of HCP provided in previous studies have been limited to specific configurations of the circuit and/or specific characteristics as needed in that study. In this article, a comprehensive theoretical analysis of the HCP circuit is performed, and it is shown that many important characteristics of the HCP can be written with respect to three main parameters of the circuit: the scale of the resistors used, the feedback ratio, and the value of the current sensing resistor in the positive feedback path.

The role of these parameters in enhancing different characteristics of the HCP is discussed, and extended to different popular configurations of the HCP circuit in a unified framework in order to compare the performance of these circuits for different applications. A series of simulations are presented to demonstrate the accuracy and the importance of the derived equations. The equations are then used to design a high performance HCP for an impedance cardiography system, as an example, and the measured performance of its practical implementation is reported to further evaluate the applicability of the equations. Moreover, the performance of the designed HCP was compared to the designs proposed in the literature. The analyses provide a deep insight into different HCP circuits, and the effect of design parameters on their performance. This further helps to design an appropriate version of HCP with optimized performance for each specific application.

2. Analysis of the standard HCP circuit

2.1. Ideal standard Howland Current Pump

Fig. 1 demonstrates the schematic of the standard Howland current pump. The load current is obtained as:

$$I_{\text{out}} = \frac{1}{R_{2b}}\frac{R_4}{R_3}\left(\frac{R_{2a} + R_2\frac{R_3}{R_4}}{R_{2a}+R_1}V_{\text{in}+} - V_{\text{in}-}\right) + \frac{R_4R_1 - R_2R_3}{R_3R_{2b}(R_1+R_{2a})}V_{\text{out}}. \quad (1)$$

where R_2 is the sum of R_{2a} and R_{2b}. If the following relationship is assumed,

$$\frac{R_2}{R_1} = \frac{R_4}{R_3} \quad (2)$$

then the load current becomes independent of its voltage and is proportional to the differential input voltage of the circuit:

$$\frac{I_{\text{out}}}{V_{\text{in}+} - V_{\text{in}-}} = \frac{1}{R_{2b}}\frac{R_4}{R_3} = \frac{1}{R_{2b}}\frac{1-\beta_{\text{fb}}}{\beta_{\text{fb}}} \quad (3)$$

where $\beta_{\text{fb}} = R_3/(R_3 + R_4)$; and the circuit becomes a voltage to current converter with differential inputs.

The compliance of the HCP is restricted by the output range of the op-amp, and can be calculated from

$$V_O = \left(1 + \frac{R_{2b}}{R_1 + R_2 - R_{2b}}\right)(V_{\text{out}} + (R_{2a}\|R_{2b})I_{\text{out}}) - \frac{R_{2b}}{R_1 + R_2 - R_{2b}}V_{\text{in}-} \quad (4)$$

Assuming $V_{in-} = 0$, Eq. (4) yields:

$$V_{out}(\max) = \frac{\left(\beta_{fb} + \frac{R_{2a}}{R_1+R_2}\right)}{\left(1 + \frac{R_{2a}\|R_{2b}}{R_{Load}}\right)}V_O(max) \quad (5)$$

Eq. (5) gives the maximum output voltage of the HCP for a constant load and therefore it determines the upper limit of the output current. The equation shows that designing the HCP with larger feedback ratio β_{fb} would increase the compliance of the circuit. This is also true for smaller R_{2b} to R_{2a} ratio since the numerator in Eq. (5) increases and the denominator decreases ($R_{2a}\|R_{2b}$ decreases when R_{2b} get smaller than R_{2a}). A small enough R_{2b} (relative to R_{Load}) also leads to the independence of compliance from changes in the output current. Note that the compliance is improved for $V_{in-} > 0$.

The design process of the Howland current pump includes selection of feedback ratio β_{fb}, scale of the resistors used in the circuit (R_3, R_4, R_1 and R_{2a}) and R_{2b} value. However, in practice there are non-ideal characteristics of the components, which affect the performance of the circuit and should be considered in the design process.