Josephson Arbitrary Waveform Synthesizer as a Reference Standard for the Calibration of Lock-in Amplifiers

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***Abstract* — We have extended the voltage range of the Josephson arbitrary waveform synthesizer from 1 mV down to 1 µV at frequencies from 60 Hz to 1 kHz to calibrate precision lock-in amplifiers. Experimental results show that the system's uncertainty is dominated by the resolution of the lock-in amplifier. We anticipate that the Josephson arbitrary waveform synthesizer-based system will extend the lower voltage and frequency range of ac voltage metrology and improve the uncertainties by one order of magnitude compared to conventional techniques.**

***Index Terms* — Voltage measurement, voltage standards, electric potential, Josephson junction, measurement uncertainty.**

I. Introduction

A Josephson arbitrary waveform synthesizer (JAWS) utilizes the accuracy of the ac Josephson effect to produce voltages calculated from first principles at frequencies up to several megahertz [1]. Behr *et al*. [2] used the JAWS to generate small voltages (from some nV to some mV). We have extended the use of a JAWS to the voltage range from 1 µV to 1 mV, at frequencies from 60 Hz to 1 kHz, to provide traceability to lock-in amplifiers. This offers a convenient and intrinsically accurate alternative to conventional methods for the calibration of lock-in amplifiers, such as those based on the generation of low voltages by means of a calibrated semiconductor source and a calibrated inductive voltage divider (IVD) [3].

II. System Description

Fig. 1 shows the block diagram of the JAWS system. The system is described in [4] and uses Josephson junction arrays (JJAs) and a microwave circuit design developed at the National Institute of Standards and Technology (NIST) [5]. The low voltages required to calibrate lock-in amplifiers are generated directly by the JJAs without any compensation signal. An arbitrary waveform generator (AWG) is used to provide an external reference voltage to phase-lock the lock-in amplifier.

III. Experimental Results

The JAWS produces quantized voltage pulses with a time integral of *h/2e* across each Josephson junction. Given that the JJA produces quantized pulses, for the JAWS to be a fundamental standard its operation must be independent of (a) the JJA used; (b) the biasing electronics (rf amplifiers and dc blocks); (c) the rf power; and, (d) the repetition frequency and the rf pattern of the pulses (i.e., if a particular waveform can be obtained by using more than one repetition frequency and pattern of pulses, the resulting waveforms should be the same). The various parts of the JJA generate sinewaves with slightly different phases due to delays in the arrival of the pulses within various parts of the JJA or the Josephson junctions, resulting in a voltage error. The last condition (d) tests for any errors due to these delays since the number of changes from a "zero" to a "non-zero" value (and vice versa) in the pattern depends on the repetition frequency.

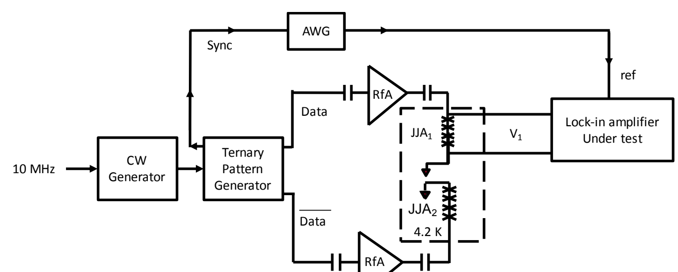

Fig. 1. Block diagram of the JAWS-based system for the calibration of lock-in amplifiers.

We conducted several experiments to provide evidence that these conditions are met. In this summary, we present some of these experiments. We used a commercial lock-in amplifier (SR865A) as a transfer standard.[1] Further experiments will be presented at the conference.

First, we investigated whether the operation of the JAWS-based system was independent of the JJA. We used the same biasing electronics (ternary pattern generator and rf amplifier) to sequentially drive two different JJAs and measured the correction of the lock-in amplifier (1 mV at 1 kHz). The results agreed within 0.08 µV, well below the resolution of the lock-in amplifier (0.1 µV for the 1 mV range).

Next, we investigated whether the JAWS system is independent of the biasing electronics and the repetition

[1]Commercial instruments and design tools are identified in this paper to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by NIST and NMIA, nor does it imply that the equipment identified is necessarily the best available for the purpose.

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frequency of the rf pattern of pulses used to generate the desired signal. We generated four waveforms with the same rms value (1 mV) and frequency (1 kHz), using four different rf repetition frequencies. We then used two different sets of biasing electronics (CH1 and CH2) to bias the same JJA sequentially and measured the correction of the lock-in amplifier (Fig. 2). The results show consistency in the measurements.

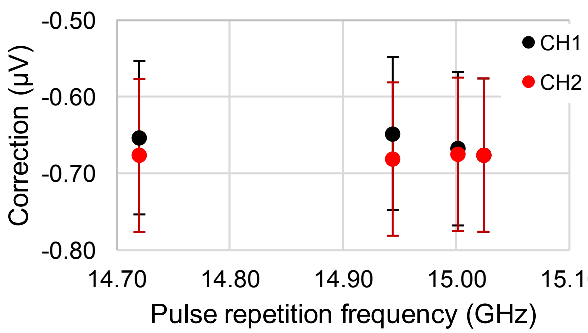

Fig. 2. Correction of the lock-in amplifier at 1 mV and 1 kHz for various pulse repetition frequencies. The error bars show the resolution of the lock-in amplifier

The quantization of the JAWS is usually checked by measuring the spectrum of the generated signal. Fig. 3 shows the spectra of these waveforms, measured with a National Instruments 5922 digitizer at a sampling frequency of 10 MHz, and the spectrum of a signal with the same characteristics produced by dividing a 1 V output voltage of a calibrator (Fluke 5700A) with an IVD (Sullivan F9200) with ratio 1000:1. Fig. 3 also shows the Fourier transform of one of the pattern of pulses downloaded to the pattern generator (for repetition frequency 15.0016 GHz) and the ideal spectrum of a Δ-Σ modulator with similar characteristics to the one used for the generation of the pattern of pulses. As can be seen from Fig. 3, the noise floor and the spurious tones of the JAWS and the calibrator/IVD signals are similar, which suggests that the various spurious tones and the noise floor in the spectrum are features of the digitizer.

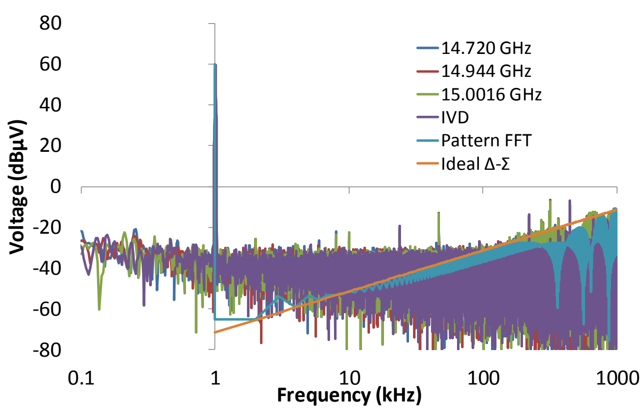

Fig. 3. Spectra of the four waveforms (1 mV at 1 kHz) produced by different means (see text for details).

The corrections of the lock-in amplifier were measured at a number of voltages in the range from 1 µV to 1 mV and at frequencies of 60 Hz, 200 Hz and 1 kHz. Figs. 4a and 4b show the results for 1 µV and 1 mV, respectively. For comparison, Figs. 4a and 4b also show the corrections of the same lock-in amplifier measured with a conventional lock-in amplifier calibration system consisting of a semiconductor source (Fluke 5700A) and an IVD (Sullivan 9700A). The results agree within the resolution of the lock-in amplifier.

(a)

(b)

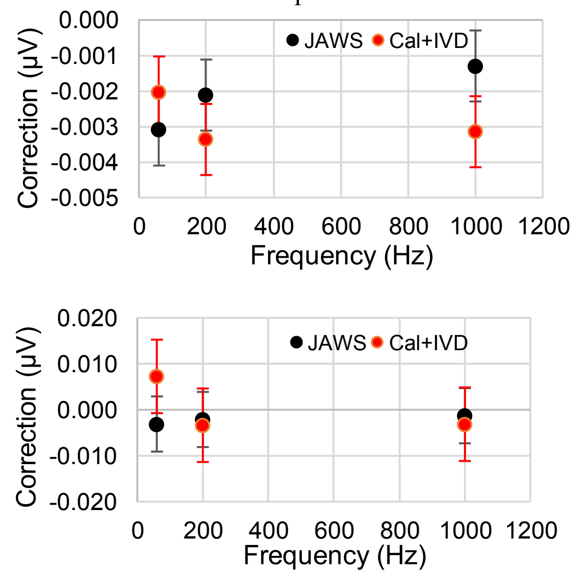

Fig. 4. Correction of the lock-in amplifier at (a) 1 µV and (b) 1 mV for different frequencies. The error bars show the resolution of the lock-in amplifier (1 nV and 0.1 µV, respectively) for the corresponding ranges.

Conclusion

The results presented in this summary show that the JAWS gives consistent results for the generation of low voltages from 1 µV to 1 mV at frequencies up to 1 kHz. The uncertainty analysis, to be presented at the conference, suggests that the dominant uncertainty component is the resolution of the lock-in amplifier under test.

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