An RF-Synthesizer for Fundamental and Precisely Adjusted Higher Harmonics

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Abstract

Recent accelerator developments favour using non-sinusoidal wave forms that can aid transition crossing or stochastic cooling of bunched beams. Generating the harmonics with analogue circuits, one faces the problem that phase shifts, impedance variations in the acceleration cavity (a complex load), etc. alter the pulse shape. The problem worsens with a swept frequency. Using an arbitrary function generator, the numerical sequence must be recomputed for every variation. We present a signal synthesis technique based on complex fourier series that allows frequency ramps preserving the waveform shape, guarantees a precise phase adjustment of better than 0.02° within a full 360° range, and 16 bit amplitude control for the harmonics. The design uses a two-stage DDS-system. An NCO (Numerically Controlled Oscillator) running at 1024 MHz clocks the digital signal processing elements and the DA-converters (DACs). Complex multipliers adjust in real time the complex values delivered by lookup-tables and feed 12 bit DACs capable of clock rates of up to 250 MHz. The NCO and the complex coefficients are computer-controlled. The thus produced signals are added, and the mixture drives the power amplifier of the connected wide band cavity. This set-up has been successfully tested; results are discussed.

1. INTRODUCTION

Traditionally designed, the rf-system of a synchrotron incorporates a frequency synthesizer, control loops, amplifier stages and one or more resonant cavities. In [1] the synthesizer part and the control loop of COSY are described which is the hardware basis for generation of higher harmonics. With a new type of broad-band acceleration structure [2] it is possible to apply these higher harmonics to a particle beam. An rf-system usually operates on an integer multiple of the revolution frequency f_a of the particle beam and, with the exception of [3], uses a sinusoidal acceleration waveform. As mentioned in [1] it is desirable to use an rf-system that allows to synthesise not only the fundamental frequency but also simultaneously higher harmonics, in this case the second and the fourth. This is a fourier-synthesis where the resulting voltage v_g across the acceleration gap is described by:

$$v_g = a_1 \cdot \cos(2\pi\, f_a t + \phi_{s1}) + a_2 \cdot \cos(2\pi \cdot 2 \cdot f_a t + \phi_{s2}) + a_4 \cdot \cos(2\pi \cdot 4 \cdot f_a t + \phi_{s4}) \qquad (1)$$

The coefficients a_1, a_2 and a_4 are the amplitudes of the harmonics and ϕ_1, ϕ_2, and ϕ_4 are their phases with respect to an absolute time frame.

2. GENERATING HIGHER HARMONICS

2.1. *Overview of the synthesizer*

With analogue mixers and phase shifters, it is nearly impossible to generate a signal according to eq. (1) when the frequency sweeps more than one octave, because their transfer functions (amplitude and phase) are frequency-dependent. Furthermore, quadrature hybrids, which are necessary for single sideband mixers (= phase shifters) only work in a narrow band regime. Suppose that one uses three synchronised NCOs operating at the fundamental and the harmonics. The synchronism is only guaranteed, if the frequency words of the higher harmonics applied to the NCOs are exact multiples of the fundamental frequency word and are valid in the same time interval. This crucial timing requirement doesn't allow a sequential frequency change. Synchronised NCOs operating at 100 MHz expect the frequency information within a timing window of about ± 5 ns. So Fig. 1 shows a different approach.

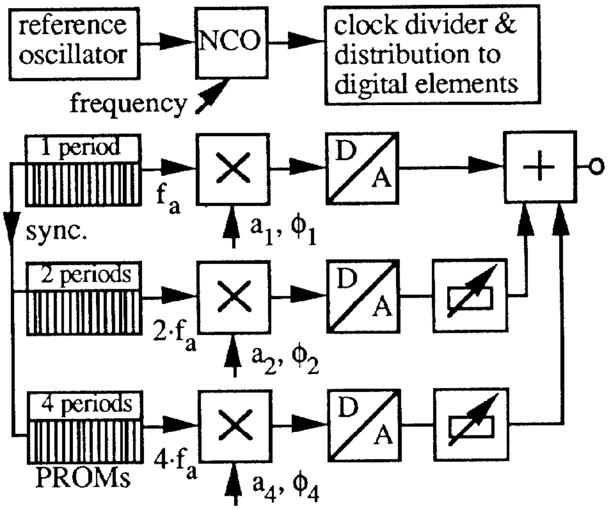

Fig. 1: Basic synthesizer layout

A reference oscillator operating at 1.024 GHz drives a GaAs-NCO to which the frequency information is applied with 24 bit resolution. The output of the NCO serves as a synchronous master clock signal for all digital components. A counter addresses tables containing time discrete values of the harmonics (h = 1, 2, 4). The samples are complex values to be multiplied with the corresponding phase and amplitude given in Cartesian co-ordinates. The harmonics - modulated in phase and amplitude - are reconstructed by DACs and added to produce the desired signal.

2.2. *Reference oscillator, NCO and clock distribution*

As mentioned before, this signal synthesis relies on a predictable transfer function of the elements in the signal path. To minimise all error sources a fully synchronous design performs the digital signal processing, where the clock frequency is an exact multiple of the revolution frequency f_a[1]. A combination of a high precision TCXO (Temperature Compensated Crystal Oscillator) with a numerical oscillator, as shown in Fig. 2. allows to separate the requirements. The TCXO guarantees accuracy and stability over environmental influences whereas the NCO allows for flexible and precise tuning.

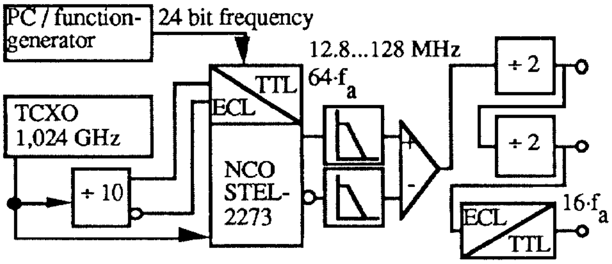

Fig. 2: Clock generation

The NCO generates a clock signal that is 64 times the revolution frequency f_a. The clock rate of $32 \cdot f_a$ drives the DACs and $16 \cdot f_a$ all other digital components. This feature implies that the algorithm operates frequency-independent.

2.3. *Lookup-tables, digital phase shifters and multiplexers*

As shown in Fig. 1, three look-up-tables contain the samples of sinusoidal waveforms. The fundamental (h=1) is stored using N = 32 values for a full period. The PROMs store two periods for the second harmonic and 4 periods for the fourth. The complex multipliers need the carriers as complex signals with sine and cosine, so both values are stored. To stay below the maximum data rate of about 32 MHz of the multipliers and to reach the needed highest frequency of the fundamental with 32 sample values, it was necessary to double all data paths and to interleave the data. Multiplexers following the multipliers combine the two streams and deliver a maximum data rate of 64 MHz to the DACs. The digital complex multipliers accept two complex 16-bit integer values as input and generate a complex product. For one carrier frequency, Fig. 3 shows the circuit layout and the correspondences between the signals. With n as the state of the counter the tables contain:

$$\begin{aligned} t_1 &= \sin(2\pi\, 2 \cdot n \cdot h \,/\, N) \\ t_2 &= \cos(2\pi\, 2 \cdot n \cdot h \,/\, N) \qquad (2) \\ t_3 &= \sin(2\pi\, 2 \cdot n \cdot h \,/\, N + 360^\circ / N) \\ t_4 &= \cos(2\pi\, 2 \cdot n \cdot h \,/\, N + 360^\circ / N) \end{aligned}$$

This circuitry is also capable of generating harmonics other than eq. 1 under the condition, that the number of samples N in the PROMs is a multiple of four and that N/4 may be divided by each harmonic without remainder. To generate the third harmonic would require N=24 sample points and a change of the frequency limits.

It is important to point out, that the phase accuracy of this arrangement only depends on the word length of the multipliers. As the components have a 16-bit word length, we obtain a phase resolution of better than 0.01°. The two's complement permits a full 2π and 2π periodic operation. In the digital signal path, no phase deviation between the channels does occur - important to obtain a predictable waveform shape.

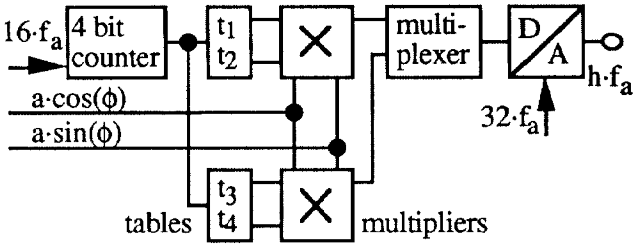

Fig. 3: Signal path of one carrier frequency

2.4. *DA-converters and analogue components*

The 12 bit wide DACs allow a maximum data rate of 250 MSPS. The DA-board is mechanically combined with the multiplexer to be a standard 6 units high VME-card. Low-pass filters of butterworth type remove unwanted harmonics and alias frequencies. Conventional attenuators allow a coarse adjustment of the output amplitude of each harmonic to preserve the digital resolution. An Op-Amp is used as summer and combines the analogue signals behind the attenuators. It must be of high-speed to minimise phase deviation. Further, it drives the 50 Ω cable to the power amplifier of the cavity.

2.5. *Interface to the function generator*

The synthesizer is controlled via a portable PC equipped with a parallel I/O-Board with 96 digital I/O-lines. The frequency is given with 24 bit resolution, so that the resolution of the fundamental is 0.12 Hz in the range from 200 kHz to 2 MHz and of the fourth harmonic is 0.48 Hz in the range from 800 kHz to 8 MHz. The amplitude a_h and phase ϕ_h of the harmonic h are given as a quadrature pair like

$$[\ a_h \cdot \sin(2\pi\ f_a t \cdot h)\ ;\ a_h \cdot \cos(2\pi\ f_a t \cdot h)\ ] \qquad (3)$$

where these values have been normalised to fit into 16 bit two's complement integer numbers. To perform a first test a program in TurboPascal controlled all variables and allowed simultaneously the ramping of frequency, amplitude, and phase to compensate for the influence of the cavity on the signal shape: a phase shift of more than 90°.

3. APPLICATIONS OF HIGHER HARMONICS

A signal according to eq. 1 helps to fulfil special requirements during the acceleration cycle. For instance, the cooler synchrotron COSY has to cross the transition energy. With a acceleration voltage having a "flat-top" (see [2] and Fig. 4) during the time the particle bunch passes the acceleration gap, almost all particles "see" the same voltage and the beam remains stable. So one could start acceleration with a sinusoidal waveform just below the transition energy, then smoothly apply the higher harmonics to create a flat-top and after transition the harmonics are smoothly reduced. This flat-top allows a slower time variation (10 ms) compared to the behaviour of a rapid phase jump from ϕ_s to $\pi - \phi_s$ in 100 µs.

Another application would be stochastic cooling having a bunched beam. Normally stochastic cooling requires a coasting beam. This synthesizer can easily generate a waveform that incorporates a region with zero voltage (see [2] and Fig. 5), so that particles crossing the acceleration gap at this time gain no energy and are not influenced, so that stochastic cooling with these particles is possible.

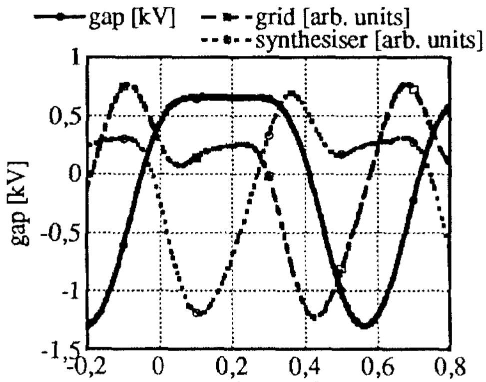

Fig. 4: Synthesised voltages for transition

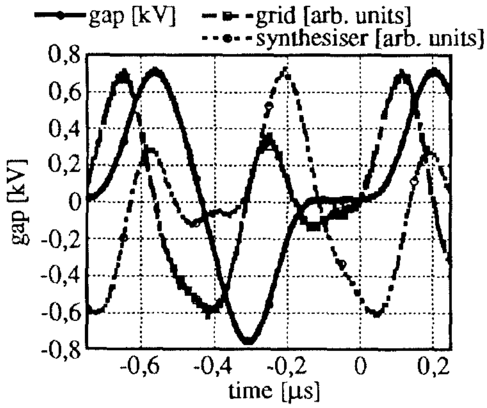

Fig. 5: Synthesised voltages for stochastic cooling

To get a feeling of the coefficients, it is necessary to perform tracking calculations with the manipulated acceleration voltage. Such a longitudinal program [4] is used to prepare for the real application of higher harmonics to the proton beam of COSY.

Experiments with a broad-band acceleration structure [2] have shown, that it is not sufficient to compute and apply the coefficients for an optimum analogue system. Instead, one has to optimise the coefficients by interactively changing them and measuring the influence on the actual acceleration voltage. For this reason, a minimum phase resolution of 0.05° was mandatory. The problems of feedback and long-term stability are not solved yet. It was possible to optimise the coefficients for several discrete frequencies. A curve fit of the values as a function of frequency allowed sweeping the frequency over two octaves with the waveform shape almost unchanged by the non-linear behaviour of the cavity. The pre-distorted synthesizer signal, the corresponding acceleration voltage ("gap") and the driving signal of the power tetrodes ("grid") are shown in Fig. 4 for crossing of the transition energy and in Fig. 5 for stochastic cooling.

Measuring the phase and amplitude relation of each harmonic component to the fundamental, it should be possible to keep the waveform stable over the full frequency range and to compensate drift effects of the analogue parts. Of extreme importance is the hysteresis of the nonlinear material used in a cavity. We hope to apply a digital control scheme, which is mentioned in [1] and in more detail in [5].
The synthesizer-design is modular and flexible (by plug-in cards), to allow the extension with a feedback algorithm. The power supply and housing was chosen to be standard VME for digital components and VXI for DACs.

4. CONCLUSIONS

A combination of a synthesizer who is able to generate precisely adjusted harmonics in real-time with a broad-band acceleration structure promises interesting acceleration experiments. However, some problems still remain, regarding the stability of the resonator as a function of temperature and drifts occurring in amplifiers and power supplies. Actually we prepare the hardware for using these acceleration voltages at COSY. If this delivers good results we have to look for the optimum feedback philosophy to step from experimental to normal operation.

5. REFERENCES

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