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AN ANALOG FREQUENCY SYNTHESIZER USING SURFACE-ACOUSTIC-WAVE READ-ONLY MEMORIES

G.Manes*, C.Atzeni**, and D.Gerli*

*Istituto di Elettronica, Università di Firenze, Firenze,Italy

**Consiglio Nazionale delle Ricerche, IROE, Firenze, Italy.

RESUME

Un générateur analogique de fréquence basé sur la synthèse d'échantillons analogiques de la partie réelle et/ou imaginaire de exp(j2π nk/N) est décrit et expérimentalement démontré. Echantillons sinusoidaux sont stockés à la sortie d'une ligne à retard à prises multiples, excitée par une oscillation sinusoidale, et sont lus à une fréquence d'horloge fixée à travers un multiplexeur analogique. La génération de fréquences discrètes est obtenue par l'adressage du multiplexeur selon multiples de l'index k.
Cette méthode pour la synthèse de fréquence représente l'équivalent analogique d'une méthode numérique, basée sur le stockage d'échantillons sinusoidaux dans une mémoire digitale. Un large nombre de fréquences peut être produit en utilisant configurations semblables à celles décrites pour la génération numérique.

SUMMARY

An analog frequency synthesizer based on generating analog samples of the real and/or imaginary part of exp(j2πnk/N) is introduced and experimentally demonstrated. Sinusoidal samples are permanently stored at the output of the N taps of a surface-acoustic-wave (SAW) tapped delay-line (TDL), driven by a CW oscillation, and are read out at a fixed clock rate through an analog multiplexer. The system thus operates like an analog read-only memory (ROM). Discrete frequency synthesis is obtained by programming the multiplexer adress sequence according to multiples of the index k. This frequency synthesis procedure represents the analog counterpart of a digital approach, based on storing sinusoidal samples in a digital ROM. Analog architectures allowing for the generation of a large set of frequencies can therefore be realized parallel to the digital frequency synthesizer configurations.

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I - Introduction

Various techniques have been devised for the synthesis of a large set of frequencies using both analog and digital approaches. A first class of frequency synthesizers is based on processing a single stable frequency source by division, phase lock, mixing[1]. A second class employs a bank of digitally selected analog filters[2], multimode oscillators[3], or discrete sine-cosine generators realized by digital recursive filters with poles on the unit circle[4]. A third class makes use of read-only memories (ROM), where frequency information is stored under various forms. In a first approach, sinusoidal samples are directly stored in a digital ROM table, and programmably read-out[5]. In a second approach, based on CZT algorithm, a set of frequencies is synthesized by multiplying two discrete chirps, stored in a ROM and read-out with a mutual delay. Both baseband[6] and r.f.[7] generation have been demonstrated using this technique.

A new discrete frequency synthesizer is described here that makes use of a tapped delay-line (TDL)-based configuration operating as a random-access ROM for storage of analog sinusoidal samples, and of a digitally controlled analog multiplexer for selection of the desired frequency. The building block of the new system consists of a TDL whose taps are accessed through an analog multiplexer, as shown in fig.1. When a signal is applied to the TDL input, samples of the signal replicas present at the individual taps are read-out according to the multiplexer adress, and appear serially reordered at the output.The device thus operates like an analog random-access memory (RAM). As described elsewhere[8], it can be used for providing variable time-base modification via the control of the multiplexer clock frequency.

II - The analog ROM

Let us now consider that a sinusoidal waveform, $\sin(2\pi ft)$, is applied to the TDL input. The replica from the n-th tap

$$\sin\ 2\pi f(t - nT_p) \qquad n = 0,1,..,N-1 \qquad (1)$$

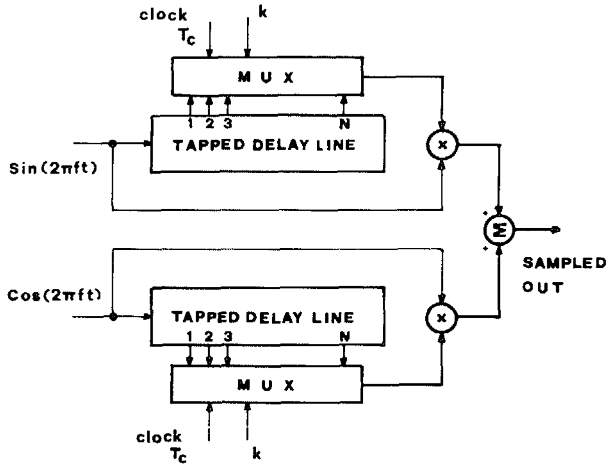

Fig. 1 - Baseband configuration of the analog ROM.

(T_p intertap delay), exhibits a phase shift of

$$\varphi_n = 2\pi T_p n \qquad (2)$$

with respect to the input waveform. Then by mixing one obtains

$$\frac{1}{2}\cos(2\pi fT_p n) - \frac{1}{2}\cos\ 2\pi(2ft - fT_p n) \qquad (3)$$

An identical unit, driven by a quadrature waveform, $\cos(2\pi ft)$, (fig.1) provides at the mixer output

$$\frac{1}{2}\cos(2\pi fT_p n) + \frac{1}{2}\cos\ 2\pi(2ft - fT_p n) \qquad (4)$$

By summing the two contributions (3) and (4), analog sinusoidal samples

$$\cos(2\pi fT_p n) \qquad n = 0,1,..,N-1 \qquad (5)$$

result permanently stored at the output from the individual taps, and can therefore be accessed at any time by programming the multiplexer adress. This arrangement of two analog RAM's, excited by phase-quadrature sinusoids, thus operates like an analog ROM.

Quadrature sinusoidal samples

$$\sin(2\pi fT_p n) \qquad n = 0,1,..,N-1 \qquad (6)$$

can be similarly stored by mixing the signal from the taps of each analog RAM with the input waveform of the other, and subtracting the outputs.

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III - Bandpass configuration of the analog ROM

The need of two quadrature channels for implementing the analog ROM is avoided when TDL's operating at r.f. are employed. Let

$$f_i = f_o + f \qquad (7)$$

be the frequency of the input oscillation. Then, the output from the mixer (fig.2 a) is

$$\frac{1}{2}\cos\left(2\pi(f_o + f)T_p n\right) - \frac{1}{2}\cos\ 2\pi\left(2f_i t - f_i T_p n\right) \qquad (8)$$

The second high-frequency term can be simply removed by low-pass filtering. By choosing

$$f_o = \frac{M}{T_p} \qquad (9)$$

with M an integer, f_o does not contribute to the value of the first term, thus yielding again the sinusoidal samples (5).

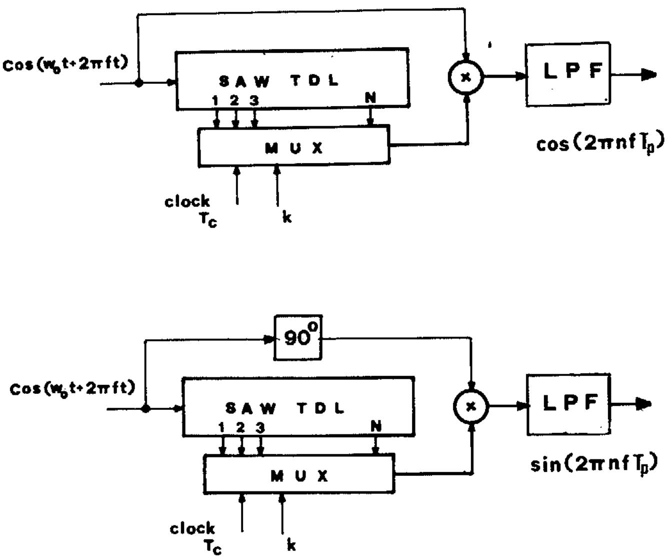


Fig.2 - Bandpass configuration of the analog ROM.
a - Generation of cosinusoidal samples
b - Generation of sinusoidal samples

In order to produce the quadrature samples (6) using this simplified configuration, it can be easily seen that the output from the TDL taps must be mixed with an oscillation in phase quadrature with the input oscillation (fig.2 b).

Surface-acoustic-wave (SAW) devices[9], which are inherently bandpass filters, provide an attractive means for implementing the r.f. TDL needed in this simple analog ROM architecture, and have been used in the reported experiments.

IV - The discrete frequency synthesizer

Let us now choose the value of f in (7) as

$$f = \frac{1}{NT_p} \qquad (10)$$

The sinusoidal samples (5) available at the output from the individual TDL taps assume the values

$$\cos\left(\frac{2\pi}{N} n\right) \qquad n = 0,1,..,N-1 \qquad (11)$$

whose argument varies in increments of $2\pi/N$ over the unit circle. By sequentially and repetitively operating the multiplexer from 0 to N-1 at a clock frequency f_c, the samples (11) are read-out repetitively at time interval $1/f_c$. As one sinusoidal period is read-out in a time N/f_c, the generated indefinite sequence of samples produces, after suitable low-pass filtering, a continuous sinusoid of frequency

$$f_1 = \frac{f_c}{N} \qquad (12)$$

If the multiplexer adress is programmed in increments of k, with k integer > 1, at the same clock rate f_c, the TDL taps are scanned one every k, thus producing sinusoidal samples

$$\cos\left(\frac{2\pi}{N} nk\right) \qquad (13)$$

at time interval $1/f_c$. An analog sinusoid of frequency

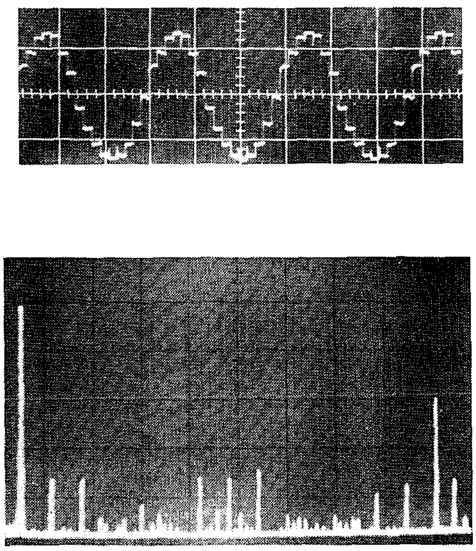
$$f_k = k\,\frac{f_c}{N} \qquad (14)$$

is so synthesized.

The maximum frequency that can be generated is limited by the sampling rate f_c to a value suitably less than $f_c/2$. The maximum number of harmonics of the lowest frequency (12) is therefore lower than N/2.

V - Experimental results

The operation of the new discrete frequency synthesizer has been experimentally demonstrated using a 16 taps SAW TDL for the implementation of a small size analog ROM. The centre frequency $f_o = 17.540$ MHz of the SAW device was ten times the inverse of the intertap delay $T_p = 0.57$ usec. According to condition (10) the frequency of the driving CW oscillation exceeded f_o by 110 KHz. In fig.3 a the sinusoidal samples read-out by sequentially switching the multiplexer gates at 1 MHz clock rate are shown. The spectral distribution of the samples sequence in the range 0 - 1 MHz is displayed in fig. 3 b. Spurious harmonics of the fundamental 62.5 KHz tone more than 35 dB down can be observed in the useful 0 - 500 KHz bandwidth.



a

b

Fig.3 - a- Sinusoidal samples read-out at 1 MHz clock frequency. Horiz. scale 5 usec/div.
b- Spectrum analyzer display of the samples in the interval 0 - 1 MHz.
Horiz. scale 100 KHz/div.- Vert. 10dB/div.

The continuous sinusoid of lowest frequency 62.5 KHz, obtained after low-pass filering with cutoff at 500 KHz, is shown in the upper trace of fig.4. Lower traces show the second and the fourth harmonic, synthesized by programming the multiplexer adress sequence in increments of 2 and 4, respectively.

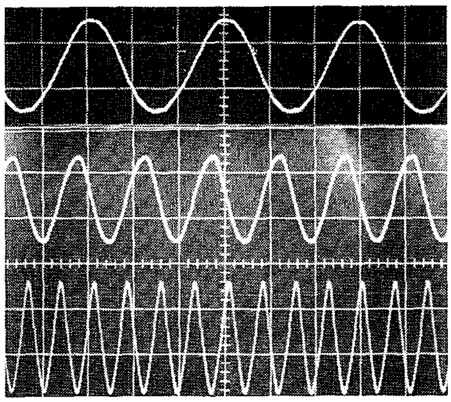


Fig. 4 - Continuous sinusoids after low-pass filtering with cutoff at 500 KHz.
Upper trace : lowest frequency (62.5 KHz)
Middle trace: second harmonic (125 KHz)
Lower trace : fourth harmonic (250 KHz)
Horiz. scale 5 usec/div.

VI - The analog vs. digital frequency synthesizer

The described analog-ROM-based frequency synthesizer appears to be the counterpart of a digital frequency synthesizer[5], based on storing in a digital ROM table samples of the real and/or imaginary part of the exponential

$$\exp\left(j \frac{2\pi}{N} nk \right) \qquad n = 0,1,..,N-1, \quad k \text{ integer} \qquad (15)$$

which are read-out at time n/f_c according to a frequency control word k. The digital samples drive D/A converters followed by a low-pass interpolating filter to produce an analog sinusoid of frequency (14).

The complete analogy of the two approaches permits to extend to the analog frequency synthesizer the unique

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capabilities of its digital equivalent. In particular, as the number of frequencies that can be produced depends on the TDL tap count, N, the above procedure becomes impractical as N increases. Following the same method described for the digital frequency synthesizer, for large N the index nk in the argument of the exponential (15) can be factored into a sum of several factors, each taking on fewer than N values. Each factor is synthesized by an analog ROM having a correspondingly lower tap count, and the outputs are properly combined using analog multipliers.

As an example, let us assume N = 100. The index nk can be written in decimal form as

$$nk = a + b.10 \qquad a = 0,1,..,9 \quad b = 0,1,..,9 \tag{16}$$

The exponential (15) can be accordingly broken into the two terms

$$\exp(j \frac{2\pi}{100} nk) = \exp(j \frac{2\pi}{100} a).\exp(j \frac{2\pi}{10} b) \tag{17}$$

The desired sinusoidal samples are so obtained as the product of two factors, each assuming ten values with argument increments of $2\pi/100$ and $2\pi/10$ respectively. To produce these increments, two identical 10-tap TDL's are required, the former driven by the frequency

$$f = \frac{1}{100\ T_p} ,$$

the latter by the frequency

$$10\ f = \frac{1}{10\ T_p} .$$

The output samples result respectively

$$\cos(\frac{2\pi}{100} a) \qquad a = 0,1,..,9$$

$$\cos(\frac{2\pi}{10} b) \qquad b = 0,1,..,9$$

A similar pair of 10-tap TDL's must be used to generate the corresponding phase-quadrature samples. Proper selection of a and b and combination of the four sinusoidal outputs allows frequencies in steps of $f_c/100$ to be synthesized.

Conclusions

An analog ROM with application to discrete frequency synthesis has been described and experimentally demonstrated. It is based on a simple SAW tapped delay-line, and is capable of generating a number of frequencies depending on the number of taps. A procedure for synthesizing a large number of frequencies using few low-tap-count TDL's has been however pointed out, using an unique approach demonstrated by other authors for a digital-ROM-based frequency synthesizer, operating according to a similar technique.

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