Quadrature Oscillator with Pre-distorted Waveforms for Application in MEMS-based Mechanical Spectrum Analyser

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Abstract:

An AC-operated capacitive accelerometer with electrostatic force feedback is employed for direct mechanical spectrum analysis. A suitable electrostatic AC field is used to make the accelerometer selectively sensitive to only the coherent mechanical frequency component. By sweeping the frequency of the drive voltage over a selected range, the mechanical (vibration) spectrum is analysed in the mechanical domain. Operation requires the simultaneous generation of pre-distorted sine- and cosine-like waveforms. A DDFS with DAC based on a specially scaled resistive string is designed, fabricated in CMOS and tested. Spurious free dynamic range is 22 dB over a frequency range DC up to 1 kHz. The spectral performance is comparable to FFT-based systems for spectral analysis on a time series supplied by a conventional accelerometer, while the overall system features a reduced complexity, simple spectral in-zooming and potential for low power consumption.

1. Introduction

Conventional techniques for condition monitoring of mechanical machines, based on vibration monitoring for early failure detection, generally use algorithms operating in the frequency domain, rather than in the time domain [1]. From a sensing perspective, two main approaches are used:

1. Vibration analysis in the electrical domain, which is conventionally implemented in a straightforward way by having an accelerometer to measure a time series and a DSP (Digital Signal Processor) to perform a FFT (Fast Fourier Transform) [2].

2. An array of tuned resonators measures the mechanical vibration. Each resonator is tuned on a specific frequency, so several spectral lines are obtained in parallel [3].

In an alternative approach a micromachined capacitive accelerometer structure is operated using electrostatic feedback with an AC drive component introduced in the loop [4]. The AC component in the excitation voltage enables the realization of a mechanical spectrum analyser with frequency selectivity in the mechanical domain. A wideband accelerometer can be made selectively sensitive to a narrow mechanical frequency component that is coherent with the electrical field induced driving force. By sweeping the electrical frequency over a selected range, the mechanical frequency components are obtained sequentially with a resolution determined by the details of the feedback loop.

Operation critically depends on the AC waveform, as the electrostatic field depends on the excitation voltage squared and on the electrode position. Moreover, the electrostatic field should be available in quadrature. The oscillator for generating the required waveforms is described here and consists of a digitally synthesized ramp to drive a non-linear DA converter based on a resistive divider string with specially designed resistor values.

2. Operating principle

The conceptual device is the conventional single-sided clamped inverted pendulum in the gravitational field, as shown in Fig. 1. The seismic mass, m, is assumed to be concentrated at the top. The clamped beam has only elastic properties. In the absence of any horizontal acceleration component, the vertical position is at equilibrium. Any horizontal inertial force causes a displacement from the vertical position, δ, until the reaction developed at the clamping point equilibrates the external action. Without a gravitational field this external action is solely determined by the horizontal force. However, in the presence of a gravitational field the effect is magnified by the force F_g (Fig. 1) and thus yields a larger equilibrium deflection.
The principle remains valid if the vertical gravitational field is replaced with an electrostatic field. The actual structure fabricated in silicon using micromachining techniques is planar, rather than vertical, and is shown in Fig. 2. The DC gravitational field is replaced by an AC electrostatic field.

A twin-accelerometer structure is used with the two identical accelerometers electrostatically driven in quadrature, which eliminates the even harmonics of the transfer function, including the DC component, by subtraction of the outputs signals of the two accelerometers. A time-multiplexing method is used to extract the real and imaginary components of the desired spectral term (2\(\omega\)) of the input mechanical vibration. By varying the frequency \(\omega\) of the electrical actuation, the mechanical vibration spectrum is scanned.

This is basically an extension of the chopper combined with coherent detector that is often used in instrumentation and measurement. However, the sine- and cosine modulation voltage need to be replaced by properly pre-distorted waveforms, as the modulation parameter (the electrode displacement, \(\delta(t)\)) is present in the feedback path rather than in the forward path. Moreover, this parameter is depending on the excitation voltage squared.

The shape of the excitation voltages required for obtaining a sinusoidal displacement of a moving electrode in an electrostatic field results from a simple analysis of the electrostatic forces in an electrostatic transducer [4,5] and is indicated in Fig. 3 (solid line). The dashed line shows the effect of quantization (number of samples per period) of the excitation voltage on the electrode displacement function. The acceptable quantisation error is specified using the frequency spectrum, \(\delta(\omega)\), in terms of the spurious free dynamic range (SFDR).

System performance critically depends on the quality of the quadrature oscillator signals. The design of this Direct Digital Frequency Synthesiser (DDFS) is discussed in the next section.
3. Design of the DDFS

The DDFS for variable frequency is based on a ramp generator plus a DA converter, as shown schematically in Fig. 4 [8, 9]. The special issue imposed by this application is the non-linear DA conversion. A generic CMOS process is used to allow IC-compatible MEMS post-processing, which precludes implementation of a ROM look-up table. A specially designed resistor string and two sets of tap switches are used for forming the proper excitation voltages. Only the part for the phase range in between 0° and 180° is generated and switching is used to synthesize the entire waveform and the quadrature component.

The excitation waveforms should be such that the associated displacement functions are perfect sine- and cosine functions (see Fig. 3). In terms of frequency diagram, for \( \delta(t) = \sin(\omega t) \), the drive voltage should contain a DC offset and a component at \( \omega/2 \).

Figure 4, Simplified block diagram of the quadrature oscillator.

The ramp with adjustable increment is generated by repetitive addition of a Frequency Control Word (FCW) in the phase accumulator, as shown in Fig. 5. The four most significant bits are used to drive the DA converter to yield the momentary value of the excitation voltage. In the present circuit \( m = 20 \) bits and a 1 MHz system clock is used to enable the generation of a ramp between 1 Hz and 1 kHz with 1 Hz resolution.

Figure 5, Structure of the Direct Digital frequency Synthesiser DDFS.

The number of output bits of the phase accumulator determines the number of samples per period and thus the magnitude of the parasitic harmonic components. Figure 6 shows the result for 8, 16 and 32 samples per period. For 8 samples/period the theoretical spurious free dynamic range between baseband and second harmonic is 46 dB. However, additional filtering of \( \delta(t) \) is difficult to achieve and the entire spectrum has to be considered, which leads to SFDR= 16 dB. The SFDR increases by 6 dB per doubling of the number of samples per period. A design based on 16 samples per period (SFDR= 22 dB) is sufficient for the intended application. Moreover, for larger values the mismatch between the resistors on the string is expected to dominate system performance.

The table below shows the scaled values, resistor configuration, actual values, and error for different samples per period.

<table>
<thead>
<tr>
<th>Scaled Value</th>
<th>Resistor Configuration</th>
<th>Actual Value</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.66818E+01</td>
<td>16 + 2 3 1</td>
<td>1.66667E+01</td>
<td>-0.090</td>
</tr>
<tr>
<td>1.63283E+01</td>
<td>16 + 2 6 1</td>
<td>1.63333E+01</td>
<td>0.031</td>
</tr>
<tr>
<td>3.85473E+00</td>
<td>11 + 1 5 3</td>
<td>3.86667E+00</td>
<td>0.310</td>
</tr>
<tr>
<td>1.26789E+00</td>
<td>3 + 2 3 5</td>
<td>1.26667E+00</td>
<td>-0.097</td>
</tr>
<tr>
<td>5.40711E-01</td>
<td>1 + 3 25 6</td>
<td>5.40000E-01</td>
<td>-0.131</td>
</tr>
<tr>
<td>2.65114E-01</td>
<td>1 + 2 12 11</td>
<td>2.65152E-01</td>
<td>0.0154</td>
</tr>
<tr>
<td>1.34629E-01</td>
<td>1 + 29 10 1</td>
<td>1.34483E-01</td>
<td>-0.109</td>
</tr>
<tr>
<td>5.88235E-02</td>
<td>1 17</td>
<td>5.88235E-02</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Figure 6, Selecting the quantisation level.
The next design challenge is the design of a resistor string to define the required quantisation levels using unit-resistors. Table 1 shows the result (16/1 +2/3 indicates 16 unit resistors in series plus two series connected sets of three unit resistors). The ideal values are scaled to a relative value and subsequently an optimum network of series/parallel connected resistors is designed. The solution is not unique, but yields a deviation from the ideal value smaller than the expected component mismatch.

4. Results and Conclusions

Figure 7 shows the 2.1x2.6 mm² die of the DDFS fabricated in CMOS. Power consumption is 5 mW at 5V and 1 MHz clock frequency.

Figure 8 shows the spectrum of the voltage generated referred to the displacement. Comparison with simulations shows an acceptable level of agreement.

First experimental vibration measurement results are shown in Fig. 9. The input acceleration waveform was generated using a vibration table and was composed of three components (70, 110 and 190Hz). A charge amplifier in CMOS was used for capacitive readout of the electrode position. The real-time spectrum extraction scheme was applied, with a 2 sec integration time for each point and compares favourably with a FFT of a time series using the same measurement time.

5. References