Hyperfine Interact (2011) 202:107–115
DOI 10.1007/s10751-011-0342-4

# Smooth driving of Mössbauer electromechanical transducers

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Published online: 18 October 2011


**Abstract** Quality of Mössbauer spectra is strongly related to the performance of source velocity modulator. Traditional electromechanical driving techniques demand hard-edged square or triangular velocity waveforms that introduce long settling times and demand careful driver tuning. For this work, the behavior of commercial velocity transducers and drive units was studied under different working conditions. Different velocity reference waveforms in constant-acceleration, constant-velocity and programmable-velocity techniques were tested. Significant improvement in spectrometer efficiency and accuracy was achieved by replacing triangular and square hard edges with continuous smooth-shaped transitions. A criterion for best waveform selection and synchronization is presented and attainable enhancements are evaluated. In order to fully exploit this driving technique, a compact microprocessor-based architecture is proposed and a suitable data acquisition system implementation is presented. System linearity and efficiency characterization are also shown.

**Keywords** Mössbauer · Instrumentation · Spectrometer · Transducers · Constant-velocity

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## 1 Introduction

Double loudspeaker-type electromechanical transducers have become a standard for Doppler energy modulation of the radioactive source in Mössbauer experiments [1–6]. These devices have proved to be reliable and relatively inexpensive. Required velocity resolution for hyperfine observations (better than 10 μm/s) can be obtained with a careful adjustment of the corresponding drive. Transducers success relies mainly on their excellent performance in traditional constant-acceleration (CA) experiments, in which case the velocity reference is a zero DC triangular voltage waveform that must be tuned to the natural oscillating frequency of the transducer. In such case the operation of the oscillating device is favored by the low harmonic content of the required velocity.

However, in constant-velocity (CV) and programmable-velocity (PV) experiments [7–9], the reference has a much higher harmonic content. This causes the performance to drop drastically, due to transient responses that deteriorate the whole spectrometer efficiency.

In the following sections we present an analysis of the velocity control problem, we propose a technique based on the manipulation of the harmonic content of the reference waveform, and finally we present the design, implementation and characterization of a programmable data acquisition system that enables the application of the proposed technique.

## 2 Operation fundamentals and characterization

Regular electromechanical transducers are damped oscillating systems that exhibit longitudinal displacements proportional to the current applied to a driving coil enclosed in a uniform magnetic field. The voltage induced on a second coil is used to sense the resulting velocity to provide a control feedback loop. Due to this derivative behavior, their transfer function presents a cusp-like frequency response [1] centered at the mechanical resonance (10–20 Hz), where minimum attenuation and phase shift occur. An electrical resonance coincident with phase inversion (near 10 KHz) limits the gain margin to 40 dB. In order to flatten the frequency response around the natural frequency, driving methods apply pole-zero compensation to provide additional 20 dB in gain margin. Feed-forward control techniques are used to improve low frequency behavior. However, low gain at high frequencies and null DC sensitivity are inherent characteristics of these devices that can not be easily overcome. Moreover, several electrical and mechanical nonlinearities further deteriorate far-from-resonance operation.

Given an abrupt change in reference, as required during CV returns and slope changes in CA mode, the low gain at high frequencies is the cause of long error stabilization periods. PV operation is more affected as it requires CV waveforms to be periodically modified during the experiment to achieve channel selection. In this case it is important to select fixed frequency operation, to avoid that a change in velocity should alter the frequency requirements imposed to the feedback system. Otherwise compensation will require adjustments, turning automatic operation unfeasible. In order to avoid that, the harmonic content of the reference waveform should remain

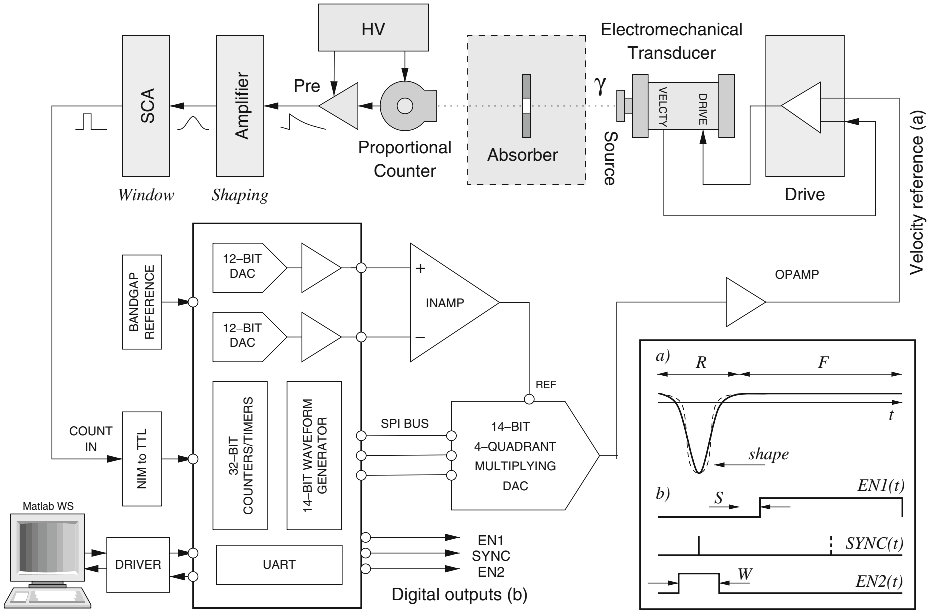


**Fig. 1** Schematic diagram of the proposed data acquisition system. Traditional driving stage and detection of resonant photons (*shaded*) are included in order to complete a programmable-velocity spectrometer. *Inset* outputs of the digital waveform generator for one period, operating in PV mode: **a** analog velocity reference and **b** digital synchronization signals required for automatic operation. All parameters ($R$, $F$, $S$ and $W$) are programmable in order to optimize transducer behavior. Return trajectory shape is also configurable so its frequency content can be tuned with control system frequency response. *Dotted line* in (**a**) represents a *softer* trajectory, with the same effective displacement than solid line, that can better suit a massive system

unaltered for all forward velocities, being restricted by the frequency characteristic of the transducer.

The solution proposed is to provide a smooth periodic flat-topped null-media waveform with the appropriate frequency content, which is linearly amplified to get the required forward velocity. Parameters of the proposed reference are shown in Fig. 1 together with the whole experimental configuration. As presented in the inset, duty-cycle $F/(F+R)$, efficiency $(F-S)/(F+R)$ and *shape* must remain constant, providing identical behavior for all channels, thus enabling programmable operation. A drawback of fixed frequency operation is the degradation of potential efficiency improvement in low velocity channels. This technique equals efficiency for all the velocity range.

Frequency content considerations can also be applied to CA operation, where velocity reference is a null media triangular voltage that introduces a transient response after the change of slope. A smooth reference can improve efficiency reducing the settling time.

In order to achieve smoothness, the velocity reference should observe as many continuous derivatives as possible. But narrowing the reference frequency content around transfer cusp implies widening the return trajectory in the time domain. Fourier transform localization property [10] shows that it is not possible to arbitrarily concentrate both a function and its frequency spectrum. An efficient velocity reference (a large flat section in CV mode) will demand a fast return movement, which will degrade smoothness.

The driving coil has a power limit given by its limited dimensions, as it must be designed to actuate inside a constant magnetic field gap, a fact that also limits the maximum allowed displacement. Then, the driving stage output power must be limited in order not to exceed these limits. In a constant magnetic field, the force (i.e. acceleration) is proportional to the driving current. Being the driving coil highly inductive, voltage is proportional to current first derivative (i.e. velocity reference second derivative). In this context, it is advisable not only to select waveforms that require a continuous voltage and derivatives. It is also important to require a limited voltage magnitude. A third derivative must also be considered in order to address output amplifier maximum slew rate. If the driving unit fails to deliver required output voltage in the feedback loop (because of coil protection or slew rate limitations) the recovery time is degraded.

In consequence, for each electromechanical transducer with a given feedback layout, there is a triple compromise between reference smoothness (minimum bandwidth), duty-cycle (minimum reversing trajectory) and third-order derivative magnitude (amplifier slew rate). As these three variables can not be minimized simultaneously, a balance must be found in order to get a maximum efficiency. It was found that the optimal waveform depends on transducer and driving unit characteristics, but some general rules can be established.

As a first practical approximation, it must be considered that transducer characteristics impose frequency and power limits to the optimal reference waveform. These limits can be roughly calculated and must be implemented within a reasonable security margin. Fundamental frequency of the velocity reference must be selected slightly below transducer resonance (that can be easily measured) in order to adjust the center of the reference frequency content with the transducer response. Additionally, transducer power capabilities limit the maximum amplitude for reversing trajectory in the highest velocity channel. Given this limited amount of deliverable power, duty-cycle and waveform are hardly related.

Once power and frequency limits are secured, CA or CV waveform must be selected in order to maximize efficiency. As shown, smoother waveforms demand the smaller driving power and can maximize useful spectrum region without saturation of the driving system. The optimal balance between softness and duty-cycle will be different for each individual transducer and driver pair.

Several functions were considered as candidates for optimal return trajectory in CV/PV operation or slope change in CA mode. A first useful group of trajectories can be built using n-order splines. In this case rising the order for a fixed duty-cycle increases softness but also increases maximum required velocity; the same behavior present the even powers of a sine half cycle. With a different approach, portions of ascending frequency sines or cosines can be combined with increasing order polynomials to form an adequate returning (i.e. two stretches of quarter period cosine superimposed to a parabola with offset can provide a continuous third derivative with moderate amplitudes). In terms of the localization property, self-dual functions [10] show a special behavior: Gaussian shaping presents the minimum product between time and frequency standard deviations; being sharp and asymptotic in the extremes, net trajectory is reduced and requires relatively high velocities at the center. Other exponential or asymptotic functions (like $e^{-1/t}$, $e^{-\exp(-t)}$, $e^{-1/(1-t2)}$, *erf* or *tanh*) can be carefully spliced together in order to compose a soft return trajectory. A more systematic method to produce trajectories is to propose an $n$-order polynomial with $n+1$ constrains (trajectory limits, null media and $m$-order continuous derivatives).

Derivatives and FFT were evaluated for these functions considering a varying duty cycle. Quantization and sampling frequency effects were also studied. A set of best performing waveforms was selected for experimental testing in commercial velocity transducers and drivers. The study was conducted using an ad-hoc designed waveform generator that was later incorporated to the spectrometer implementation that will be presented in the last section. It implements memory stored tables with different high resolution base shapes, programmable duty-cycle and efficiency, null-media, and full dynamic range resolution for all velocities. Its output can be externally amplified preserving resolution (14-bit) for channel selection. Sampling frequency (200 KHz) was selected well above sensitivity of the electromechanical transducers. Response to selected waveforms was tested for two different configurations: (a) Austin Science Associates K-3 linear motor with drive unit, and (b) WissEl MA250 velocity transducer with MR350 drive unit. Both arrangements exhibited comparable behavior. Imposing up to a continuous third-order derivative gives the best performance, as increasing this order, even though improving smoothness, unnecessarily forces the slew rate of the driving amplifier. Shapes of a fourth power of a sine semi cycle present also a good behavior, presenting a short underdamped transient response. Efficiencies up to 75% for the first arrangement and 85% for the second were achieved in both horizontal and vertical layouts.

## 3 Synchronization and stability considerations in PV mode

Being reversing time not negligible in CV/PV operation, inhibition for the counting system must be provided by the waveform generator during $R+S$ reversing interval (see Fig. 1 inset). Both counter and live-time timer must be paused while the transducer returns and stabilizes the recording velocity. Digital *EN1* signal can be used to implement this functionality. Duty-cycle of *EN1* is equivalent to counting efficiency, as usual in CV operation. But in order to achieve efficient programmable operation, two additional timing aspects must be considered.

Channel selection is accomplished by proportionally amplifying the base reference waveform. In order not to alter the mean value of the pickup displacement, channel changes must be performed either gradually, what is time consuming, or in precise synchronization with the trajectory. Given the limited low frequency sensitivity, a DC perturbation would only be addressed by the pickup springs, introducing a long term stabilization interval of several periods. Changing amplitude exactly in the trajectory center is the only way to avoid this problem, as a change in waveform amplitude does not require a change in position. When a new velocity is requested to the generator, it must be held until the center of the trajectory is reached. With that purpose a second synchronization signal must be provided by the generator, indicating it is ready to accept changes, as shown in Fig. 1 inset (*SYNC*). The reversing trajectory center is preferred, with the drawback of being the maximum velocity point. If transient response can not be stabilized, forward trajectory center can be used (dotted *SYNC*), with the drawback that channel commutation must be implemented while recording.

Under certain circumstances the CV/PV return trajectory can also be used to record resonant absorption (reverse-counting technique). This can be used to improve efficiency, but some remarks must be done regarding the usefulness of the results. As velocity precision can not be guaranteed in this region, it must be taken into account that reference is only an approximation of actual velocity. Despite this uncertainty, the technique can be useful for background recording. For example, if absorption has been recorded in the last absorption line of a sextet, experimentalist can be confident that negative-half background rate is being recorded during the fastest return path (when duty cycle is 80%, maximum return velocity is about four times the programmed velocity). To exploit this characteristic, a second ratemeter and a digital vetoing signal can be added to count events that occur only during the fastest return zone. This inhibition signal must be symmetrical with the trajectory center during the return path (maximum velocity), with a single programmable parameter $W$ (see *EN2* in Fig. 1). If reverse-counting provides useful information, instrument efficiency can be redefined as $(F + W - S)/(F + R)$ and it can be considered to provide a direct measurement of relative resonant absorption. In a real application (e.g. sixth line temperature tracking) a 10% $W$ can be used to rise from 80% to 90% the spectrometer efficiency. In such a case, every eight cycles at programmed velocity (forward-counting), one equivalent background channel will be obtained with reverse-counting.

This technique can also be used to mitigate stability issues that are present during PV operation. This mode enables the recording of a single channel of the spectrum for an arbitrarily long period of time before moving to the following point of interest. If background rate is not being recorded, eventual changes in the emission rate (i.e. due to thermal instability) can not be differentiated from resonant absorption changes [12]. Moreover, radioactive source fading can not be neglected for long term experiments dealing with small Mössbauer effects, being mean life of $^{57}$Co of about one year (i.e. 0.3%/day). These inconveniences are not present when the whole spectrum is swept several times per second (as in CA mode), as the effect of a slow counting rate drift is spread uniformly in all the channels, keeping the spectrum shape unaltered. An additional background channel can be recorded under PV operation in order to monitor these phenomena, but efficiency will be degraded if only a few channels of interest are being considered. Background reverse counting can be a good alternative in such cases. For the same reason, if several channels are being recorded in PV mode, alternating between them at relatively small intervals is advisable.

## 4 Implementation of a programmable data acquisition system

An implementation in the form of a programmable-velocity scaler (PVS) is presented. It integrates the programmable digital waveform generator, a synchronized multichannel counter and a serial interface. Nuclear Instrumentation Module (NIM) standard was used for final implementation.

PVS is designed as a direct replacement of the usual Multichannel Scaler (MCS) in Mössbauer experiments. Figure 1 shows a schematic diagram of the scaler. Its main components are a 14-bit 4-quadrant precision multiplying DAC and a 32-bit RISC microcontroller that includes two embedded 12-bit DAC and several 32-bit timer/counters. Programmable base waveforms are stored in microcontroller memory and sent to DAC via SPI bus. Chanel selection for PV mode (or amplitude for CA mode) is accomplished by driving the external DAC reference with both embedded DAC through an instrumentation amplifier (INAMP), preserving shape. Additional circuitry is provided for NIM pulse conditioning and output stage.

The module supports CA, CV and PV operation modes. PV operation is based in velocity/live-time pairs. While counting photons from the SCA (forward and reverse, using enable signals), the reference is driven for the required number of cycles in order to get the live counting time. Once live-time is reached, both forward and reverse counting are returned through the serial link. The module is ready to accept a new velocity/live-time request, while keeps driving the transducer in the last velocity with halted ratemeters. When the new request is accepted, reference is synchronously updated and counting restarts.

User interface was designed to interact with high level scientific programming languages that provide tools for experiment setup, on-line control and dynamic observations. Since no hard real-time restrictions exist (a delay in serial communications degrades overall efficiency but not quality of the results) any high level language that can handle serial links can be used for building a custom application program. An I/O library was developed including procedures for the basic functionality. Additional functions were also developed to aid in measurement automation, like region of interest recording, channel swept, etc. Combining these tools with high level programming language capabilities, advanced real-time processing can be achieved in a medium-sized workstation without considerable efficiency degradation. For example, a least squares spectrum fit can be used every minute for measurement monitoring, introducing a negligible efficiency loss. A lower-level language implementation of the library is also available for embedded applications development.

## 5 Performance and applications

In order to characterize efficiency, linearity and energy resolution of the instrument in PV mode, a contrast procedure was conducted. A well known spectrum was recorded with traditional equipment and compared with the same spectrum recorded with the new scaler. Both calibrations were performed recording a complete $\alpha$-Fe 12 μm iron foil spectrum for one hour. A range from -8 to 8 mm/s was programmed in both cases. Common instrumental to both experiments was proportional counter, $^{57}$Co source mounted on MA250 transducer with MR350 driving unit, 142PC preamplifier, 572A amplifier and 420A single channel analyzer. The detection system was set in order to output $10^4$ $s^{-1}$ background rate.

The CA spectrum was recorded with a Nucleus MCS-II multichannel scaler board operating in 1,024 channels (512 after folding). The PV spectrum was taken replacing MCS for PVS (with 85% duty-cycle and 80% efficiency) where 512 channels were swept at one second per channel. Figure 2 shows the normalized superposition of both results. All six absorption minimums resulted coincident in less than one channel, evidencing excellent linearity and resolution. Regarding efficiency, programmable-velocity spectrum accumulates 80% of the statistics, a fact that is not evident in the figure. Repeatability resulted satisfactory providing detector thermal stability.

In a closer look (see fifth line detail in Fig. 2) the new spectrum presents sharper lines. After fitting considering the sample thickness, PV line width reduces from

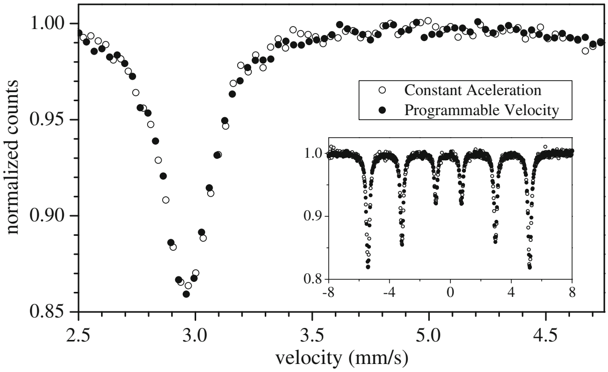


**Fig. 2** Superimposed plot of CA and PV calibration runs on $\alpha$-Fe 12 μm iron foil for one hour at room temperature. The first one (*open dots*) was recorded with a Nucleus MCS-II board and the second one (*solid dots*) with the new scaler operating in PV mode, using common detection and driving systems. In the *inset*, full range evidences equivalent linearity and energy resolution. The main figure presents a detail of the fifth absorption line, evidencing a small improvement in line resolution that can be explained based on the different operational mode

$0.214 \pm 0.006$ to $0.208 \pm 0.006$ mm/s and sixth line relative effect increases a 2%. This small improvement originates in the CV operational nature. For each CA interval the velocity reference is a ramp between two consecutive channels, not a constant, so counting occurs in an energy interval rather than in a single energy. Every CA channel records the mean absorption within this small velocity range. Alternately, CV technique holds a single energy value for the entire counting interval, providing enhanced resolution. This is evidenced by deeper lines that improve signal to noise spectrum ratio, compensating in part the efficiency loss due to CV operation.

The programmable capabilities of this instrument have been successfully applied to the determination of magnetic hyperfine field temperature dependencies [11, 12], crystallization kinetics [13] and Fe magnetic moments dynamics [14]. The ability to interact with a high-level algorithm between absorption records (channel/live-time pairs) expands the application scope to dynamic experiments. For example, a group of selected channels can be displaced in energy while the spectrum region of interest shifts in energy as a consequence of some external parameter manipulation (e.g. temperature). Mössbauer Line Tracking (MLT) is a recently developed technique [15–17] designed to continuously locate a resonant absorption line during the experiment. In such application the counting efficiency is critical since it imposes dynamic limits. Reducing the time per channel or the number of recorded channels can help to improve responsiveness at expenses of increasing statistical uncertainty. Programmable capabilities of the presented equipment open a door for discussions on optimal region of interest design [18].

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