DATA ACQUISITION AND PROCESSING FOR PTB'S IMPACT FORCE STANDARD MACHINE

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ABSTRACT

The 20 kN Impact Force Standard Machine (IFSM) of PTB’s working group “Impact Dynamics” is supposed to provide traceability for dynamic force by measuring the acceleration of a steel body using a laser-Doppler-interferometer (LDI) [1]. The acceleration itself is derived from time dependant velocity data by numerical differentiation, which is a process prone to noise amplification. Therefore a thorough investigation of the data flow and data analysis algorithms concerning robustness, accuracy and the proliferation of disturbances is necessary. This paper describes the data acquisition system together with three different algorithms for digital demodulation of the LDI signal with regard to the boundary conditions given by the parameters of the equipment.

1. INTRODUCTION

The basic set-up of PTB’s IFSM was already described in [2], where as the latest modifications including the implementation of grating interferometry are published in [3]. Therefore this contribution is focused on those components of the system which are vital for the signal conditioning, data acquisition and analysis of the acceleration determined from the LDI measurement. In order to get a better understanding of the interaction of analogue signal conditioning and digital data processing a simulation tool (ST) was designed (Fig. 2). It allows for the comparison of an acceleration signal of well-known shape as an input with the resulting acceleration after the signal processing. The input acceleration is given by either a half-sine of specified amplitude and duration or as the result of a numerical simulation of a coupled mass-spring-system under impact conditions (c.f. [1]). The latter was implemented in order to get more realistic spectral properties with the simulated signal. From this input data a simulated LDI signal is generated, which can be contaminated with certain disturbances like noise, jitter, drift or finite sampling resolution. In order to estimate the proliferation of such influences with the applied algorithms and their influence on the measurement result the original input acceleration is compared to the calculated output acceleration.

2. SIMULATED LDI SIGNALS

The LDI of the IFSM is a heterodyne vibrometer (Polytec OFV303/3000) which utilizes a Bragg cell frequency of 40 MHz. This provides the carrier for the frequency modulation generated by the Doppler shift or the phase modulation generated by the displacement, respectively. The interpretation is depending on the demodulation approach.

Due to the fact that the data acquisition system only allows for a maximum sampling rate of 10 MS/s, the maximum allowable frequency is limited to 2,5 MHz (f_{max}) in the system. This is ensured by down-mixing of the carrier frequency with 41,25 MHz (f_M), which provides a difference frequency of 1,25 MHz (f_c) as new carrier, and by limiting the line of sight velocity to less than 0,4 m/s which limits the Doppler shift (f_D) to less than 1,25 MHz . The down-mixed signal is sampled by a transient recorder at 5 MS/s or 10 MS/s and analyzed offline (c.f. Fig. 1).

The ST starts the simulation with the parameters of the down-mixed signal. I.e. it calculates a frequency modulated (fm) time series with a carrier frequency of f_c and a time-dependent Doppler shift derived from either the momentary velocity given by the integrated half-sine acceleration pulse or by the result of the solved equation of motion of the mass-spring-system.

All these calculations, together with the following analysis procedures, are embedded in a single LabVIEW® application (c.f. Fig. 2).

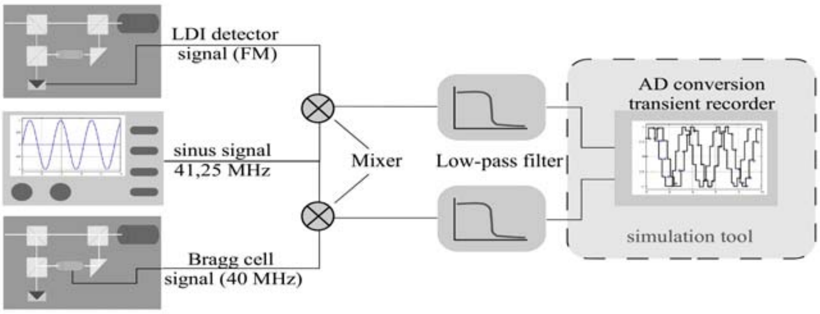

Figure 1: Analog signal conditioning and data acquisition for the velocity and acceleration measurement.

For the solution of the equation of motion a simple Runge-Kutta procedure provided by LabVIEW® is used. The resulting velocity is integrated to a displacement value which in turn is converted to a phase shift $\varphi(t)$. This phase shift is added to the phase of the carrier and passed as argument to a sine function. Thus the simulated LDI signal is composed as

$$I(t) = I_0 \sin\left(2\pi f_c t + \frac{4\pi}{\lambda}\int v(t)dt\right) \qquad (1)$$

where I_0 represents an adjustable amplitude of the signal which is typically about 0,2 V and λ is the wavelength (632,8 nm) of the LDI utilised in measurements.

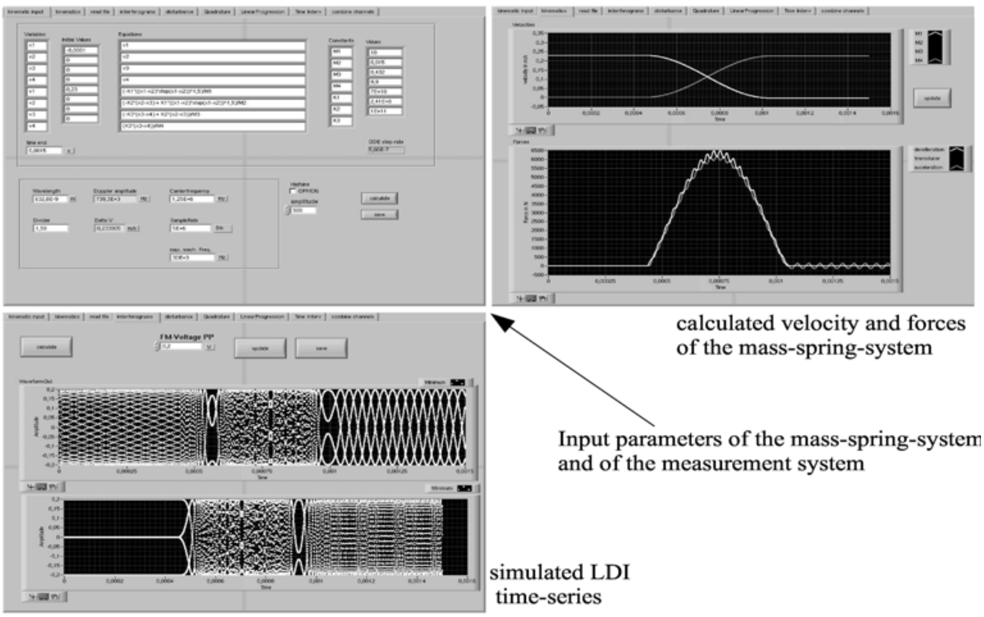

Figure 2: Screenshots of the Simulation Tool (ST) software for signal generation and analysis.

Since these digital data are on principle discrete the individual samples are given by

$$I_k = I_0 \sin\left(2\pi f_c k\tau + \frac{4\pi}{\lambda}\frac{\tau}{6}\sum_{j=1}^{k}(v_{j-1} + 4v_j + v_{j+1})\right) \qquad (2)$$

where τ is the sample interval and k is the number of the actual sample.

The main purpose of the whole simulation is the investigation of the analysis algorithms concerning disturbances. Thus different kinds of disturbances were superposed to the simulated LDI signal.

1) white noise:

For the simulation of measurement noise a uniformly distributed pseudo-random noise generator from LabVIEW® was used. With a given noise amplitude of n %, it produced uniformly distributed samples in the interval of [-0,01·n·I_0 ; 0,01·n·I_0], which were added to the original samples I_k .

2) drift:

A linear drift is simulated as a linearly increasing offset added to the original samples. The amplitude of this offset is zero at the start of the time series and 0,01·d·I_0 for the last sample, where d is an adjustable parameter.

3) jitter:

Since jitter has its origin in the timing uncertainties of the measurement it cannot be subsequently superposed to the signal. Instead, the calculation of the simulated interferogram was changed in a way that a random value δ_k was added to the time values passed to the right side of equation (2) and the interferogram was recalculated as

$$I_k = I_0 \sin\left(2\pi f_c (k\tau + \delta_k) + \frac{4\pi}{\lambda}\frac{\tau}{6}\sum_{j=1}^{k}\left(v((j-1)\tau + \delta_{j-1}) + 4v(j\tau + \delta_j) + v((j+1)\tau + \delta_{j+1})\right)\right) \quad (3).$$

For reasons of efficiency the velocity values were calculated by linear interpolation.

4) finite digital resolution:

The finite digital resolution of m bit of the ADCs in the transient recorder was taken into account by a scaling of the final simulated LDI signal to an interval of [0; 2^m-1] with subsequent rounding up and rescaling to the original range. Thus only 2^m different levels were represented in the output. However, in a real measurement this represents a usage of the ADC with optimum gain. Accordingly, with an 8-bit ADC an effective digital resolution of 6-bit (m=6) or 7-bit (m=7) is typically achievable.

3. DEMODULATION ALGORITHMS

The simulated LDI signal with or without disturbances is used as the input for the three different demodulation algorithms under investigation. Flowcharts of all three procedures are depicted in Fig. 3.

The first is a direct phase calculation algorithm using a digital quadrature and phase unwrapping scheme. Therefore, the sinusoidal input is multiplied with a digital sine and cosine of frequency 0,5·f_c and low-pass filtered to generate two time series s_i and c_i, respectively, in quadrature. The $arctan(s_i / c_i)$ with subsequent phase unwrapping represents the actual phase plus the remaining carrier of frequency 0,5·f_c. After subtraction of the linear phase generated by the carrier the optical phase-shift remains, which is proportional to the displacement measured by the (simulated) LDI. In order to calculate the wanted acceleration the displacement needs to be differentiated twice with respect to time (see below).

The second algorithm is a progressive implementation of the four parameter sine wave fit as described in [4]. In short terms it fits a function

$$I(t) = a\sin(\hat{\omega}t) + b\cos(\hat{\omega}t) + c - \Delta\omega(At\sin(\hat{\omega}t) - Bt\cos(\hat{\omega}t)) \quad (4)$$

iteratively with subsequent correction of $\hat{\omega}$ with $\Delta\omega$ until the correction vanishes (e.g. $\Delta\omega < 10^{-11}$). Then $\hat{\omega}$ represents the actual angular frequency. Progressive means that the basic fit algorithm is applied to a short section of m samples of the LDI signal and than progresses forward one sample to fit again and so on until the whole time series is processed and a series of N-m values of $\hat{\omega}_k$ is calculated. Since the actual velocity is given by

$$v_k = \left(\frac{\hat{\omega}_k}{2\pi} - f_c\right)\frac{\lambda}{2},$$

only a single differentiation is necessary to derive the wanted acceleration in this case.

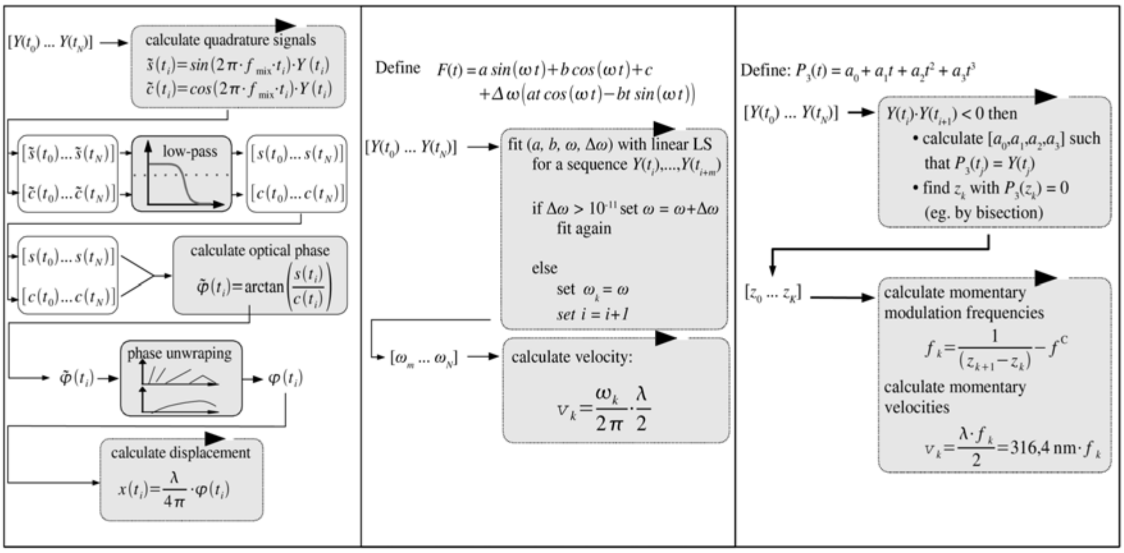

Figure 3: Flowcharts of the three demodulation algorithms, digital quadrature scheme (left), progressive four-parameter sine wave fit (centre) and digital time interval analysis (right).

The third algorithm also calculates the actual velocity from the frequency of the signal, however it evaluates the zero-crossings of the LDI-signal for that purpose. This so-called time-interval analysis (TIA) uses two samples before a zero-crossing and two samples after this crossing and fits a third-order polynomial to this values. The instant of the zero-crossing of the simulated signal is approximated by the zero-crossing of this polynomial in the interval between the second and the third sample. An estimate of the actual frequency of the signal is given by the inverse of the time interval $\tau_{Z,i}$ between consecutive crossings. It needs to be mentioned that this procedure results in a non-equidistant time series of frequencies $f_k = 0{,}5/\tau_{Z,k}$, since the instant of a zero-crossing depends on the actual frequency. Again, the actual velocity is given by $v_k = (f_k - f_c)\frac{\lambda}{2}$ and only a single differentiation is necessary to determine the wanted acceleration.

4. DIFFERENTIATION

All the specified digital demodulation procedures need at least one subsequent numerical differentiation to calculate the target measurand i.e. the acceleration. Since numerical differentiation is a process that amplifies noise to a great extent, some kind of filtering is obligatory in order to get meaningful results. For the calculation of the raw derivative a simple difference formula $Y_i' = (Y_{i+1} - Y_{i-1})/(2\tau)$ is used. To provide for the necessary noise reduction, low-pass filtering with respect to mechanical frequencies is applied afterwards. The filter consists of a Bessel-type low-pass filter with adjustable order and cut-off frequency. For comparison reasons, all signals, i.e. acceleration from the demodulated LDI and reference acceleration, were passed through the same filter.

5. COMPARISON AND RESULTS

For the comparison and estimation of the influence of disturbances half-sine acceleration pulses of 50 m/s², 100 m/s², 500 m/s² and 1000 m/s² amplitude with 0,5 ms duration were converted in simulated LDI signals. The disturbances described above were superposed on this time series and the different demodulation schemes were applied to derive the acceleration data in the same way as in a real measurement. From this results the original half-sine pulse was subtracted and the root mean square value (RMS) of the residual time series was calculated.

From the multitude of adjustable parameters and their respective combinations, only the influence of a few can be described in this contribution. In order to expose primarily the basic properties of the algorithms and the major influences, only results for a half-sine reference pulse will be given here. Also, the carrier frequency of 1,25 MHz, the sample rate of 5 MS/s and the cut-off frequency for the low-pass filter of 30 kHz with an order of 4 are fixed for the described results. In the case of the progressing four-parameter sine approximation method, a subsequence length of 51 samples was used representing roughly 10 periods of the sinusoidal LDI signal.
In a first check, the undisturbed LDI signal was evaluated by all three algorithms described in order to see any remaining residual deviations which can not be attributed to the disturbances introduced later. The results are documented in Table 1.

Table 1: Residual deviations without introduction of disturbances

Amplitude in m/s²	RMS in m/s²		
	Quadrature	Prog. Sine Fit	TIA
1000	$1{,}9\cdot10^{-5}$	$1{,}6\cdot10^{-3}$	0,06
500	$1{,}0\cdot10^{-5}$	$7{,}2\cdot10^{-4}$	0,03
100	$2{,}3\cdot10^{-6}$	$1{,}8\cdot10^{-4}$	0,01
50	$1{,}1\cdot10^{-6}$	$9{,}0\cdot10^{-5}$	0,01

This part of the investigation already revealed two vital disadvantages of the TIA algorithm. First, the algorithm is very slow, i.e. it consumes more than ten times the execution time compared to the others. Second, and even worse, the residual deviations are one to three orders of magnitude larger than those of the other two algorithms. The reason for this is the small number of samples per period of the LDI-signal which is rather close to the Nyquist-limit and not sufficient for a polynomial approximation. Therefore no further inspection of this procedure was performed and the following parts focus on the remaining two algorithms, i.e. quadrature scheme and four-parameter sine fit, respectively.
The influence of noise was evaluated for the acceleration amplitudes given in column 1 of Table 1. For noise levels of 1 %, 2 %, 5 % and 10 % of the LDI signal's amplitude no dependency of the RMS from the acceleration amplitude was observed. For both algorithms the dependency of RMS from the noise level was linear and in the range of 0,01 m/s² to 0,05 m/s². This corresponds to a peak deviation in the range of 2 m/s² to 10 m/s².
Drift was simulated for 2 %, 5 % and 10 % of the signal's amplitude (d=1, 5, 10). Although these are exaggerated magnitudes for a typical drift, the evaluation exposed no influences on the result of the four-parameter sine fit, the RMS values were of the same order as those given in Table 1 as residual deviations. For the quadrature scheme however, there was a distinctive dependency for acceleration amplitudes of 500 m/s² or more. The data displayed in Fig. 4 show the increase of RMS with rising drift amplitude as well as with rising acceleration amplitude. For amplitudes of 100 m/s² and below the RMS were not above the residual deviations given in Table 1. Nevertheless, the RMS values of the quadrature scheme were still smaller than those of the sine fit procedure.
For the evaluation of jitter influences, random time-shifts of up to 2 %, 5 % and 10 % of the sample interval τ were introduced into the velocity data used for the synthesis of the LDI signal. This random time-shifts could be interpreted as random noise with non-uniform distribution. The evaluation accordingly reveals a similar influence as it was already observed in the case of uniformly distributed noise, with a range of RMS of 0,01 m/s² to 0,05 m/s².
As far as the digital resolution of the utilised ADCs is concerned, the simulation showed that with an effective resolution of 6 bit, which is easily achievable even with today's common 8-bit ADCs, the RMS was in the order of $5\cdot10^{-3}$ m/s². With the next generation of ADCs of 12 bits sampling depth, which may achieve 10 bits effectively, the influence on the RMS could be reduced to less than $5\cdot10^{--4}$ m/s².

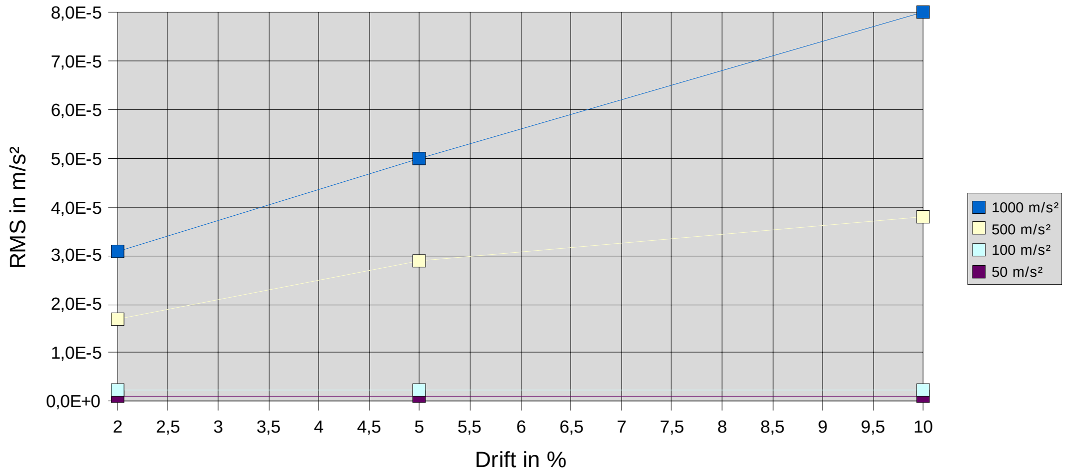

Figure 4: Influence of drift on the results of the quadrature demodulation algorithm.

CONCLUSION

Of the three different demodulation procedures described in this contribution two proved to be equally suitable for the calculation of acceleration from LDI signals. Only the time interval analysis was neither accurate nor efficient enough to compete. This, however, is due to the fact that the data acquisition system does not supply enough samples per period for an accurate approximation near the zero-crossing. The well established quadrature scheme can be utilised offline with high efficiency and accuracy as expected. Concurrently, the four-parameter sine fit might be used with slightly less efficiency but similar accuracy. This method, which is new in the context of the demodulation of LDI signals, left the impression of a smaller susceptibility to distortions of the modulated input. In conjunction with fast hardware, it might additionally provide the ability for streaming (online) velocity and acceleration calculation, which would be a valuable improvement for measurements in this field.

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