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New NIST Acquisition System for Reading Charpy Machine Encoders

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New NIST Acquisition System for Reading Charpy Machine Encoders

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Abstract

A new acquisition system was developed at NIST for reading angle values from the digital encoders of the three Charpy reference machines in Boulder, Colorado. The associated *LabVIEW* software provides the conversion from encoder angles to absorbed energies, and allows quantifying energy losses due to windage and friction through the execution of five free swings. The accuracy of the new acquisition system was verified by comparing Charpy test results obtained using both the old system (Tinius-Olsen encoder boxes) and the new system (National Instruments DAQ board + *LabVIEW* software).

Keywords

Absorbed energy, acquisition system, Charpy test, digital encoder, *LabVIEW* software.

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1. Introduction

The main outcome of a Charpy test is the energy required to break the specimen, or absorbed energy (*KV*), expressed in J. Additional results that may or may not be required are lateral expansion (*LE*), in mm, and Shear Fracture Appearance (*SFA*), in %.

Traditionally, the most common way to record absorbed energy during a Charpy test was reading the value on a graduated scale, where a needle would indicate the energy corresponding to the highest angle (rise angle) reached by the swinging hammer after fracturing the specimen. Modern Charpy machines are equipped with a digital display that automatically returns the value of absorbed energy in energy units, based on the rise angle read by a digital encoder. An encoder (also known as rotary or shaft encoder) is an electro-mechanical device that converts the angular position or motion of a shaft or axle (in this case, the pendulum hammer) into analog or digital output signals.

All the machines in the NIST Charpy Laboratory in Boulder, Colorado, are equipped with digital encoders. Three of these machines (identified as SI3, TO2, and TK) are considered *reference machines* in the ASTM E23 standard [1]. They are used to certify lots of reference Charpy specimens of various absorbed energy levels, which can be tested to perform the indirect verification of an impact machine in accordance with ASTM E23 or ISO 148-2 [2]. For a verification lot, the certified value of absorbed energy is established as the grand mean of between 75 and 150 tests performed on each reference machines.

In the early years of the NIST Charpy Machine Verification Program, which started in 1989 when NIST took over from the Army Arsenal in Watertown, MA, energy values were recorded from the analog scales of the three machines (Figure 1), after compensating for friction and windage losses by performing a free swing (*i.e.*, swinging the hammer without a specimen in place).

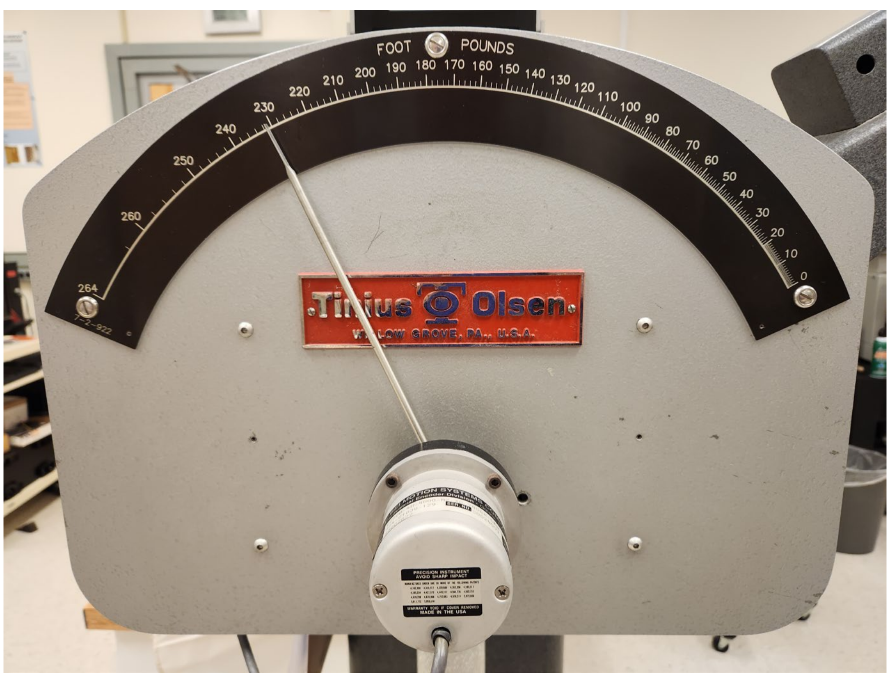

Figure 1 - Example of analog scale for the TO2 reference machine at NIST in Boulder. In this case, absorbed energy is indicated in foot-pounds.

In the mid-1990s, NIST installed digital encoders on the three reference machines, as well as Tinius-Olsen Model 892 Impact Displays (familiarly referred to as "encoder boxes") that were used to record the energy spent for fracturing the specimen (Figure 2). Absorbed energies were calculated on the basis of the latched height of the hammer (corresponding to the fall angle), the maximum post-impact height of the hammer (rise angle), and the frictional losses of the machine. For a series of tests, the boxes could also provide the mean absorbed energy and its standard deviation. The boxes could also be connected via RS232 port to a printer or a computer for data logging and analyses.

Figure 2 – Model 892 Impact Display (T-O encoder box) for one of the NIST reference machines.

The calculation of absorbed (fracture) energy from angle readings of a digital encoder consists of the following steps (Figure 3).

The potential energy (E_{pot}) corresponding to the latched position of the hammer is given by:

$$E_{pot} = mgh_1 \ , \tag{1}$$

where: m = pendulum mass (kg), g = acceleration of gravity (m/s²), and h_1 = hammer fall height (m), which corresponds to:

$$h_1 = L[1 + \sin(\alpha - 90°)] \quad , \tag{2}$$

with: L = hammer length (m) and α = fall angle (°). Substituting eq. (2) into eq. (1) gives:

$$E_{pot} = mgL[\sin(\alpha - 90°)] \ . \tag{3}$$

Note that m and L are characteristic parameters of the specific Charpy machine, while the angle α is measured by the encoder in the latched position (position A in Figure 3).

Position B in Figure 3 represents the contact between hammer and specimen, and it must correspond to the zero angle of the encoder. To make sure about this, it should be possible to reset (zero) the encoder reading with the pendulum in the free hanging, or vertical, position.

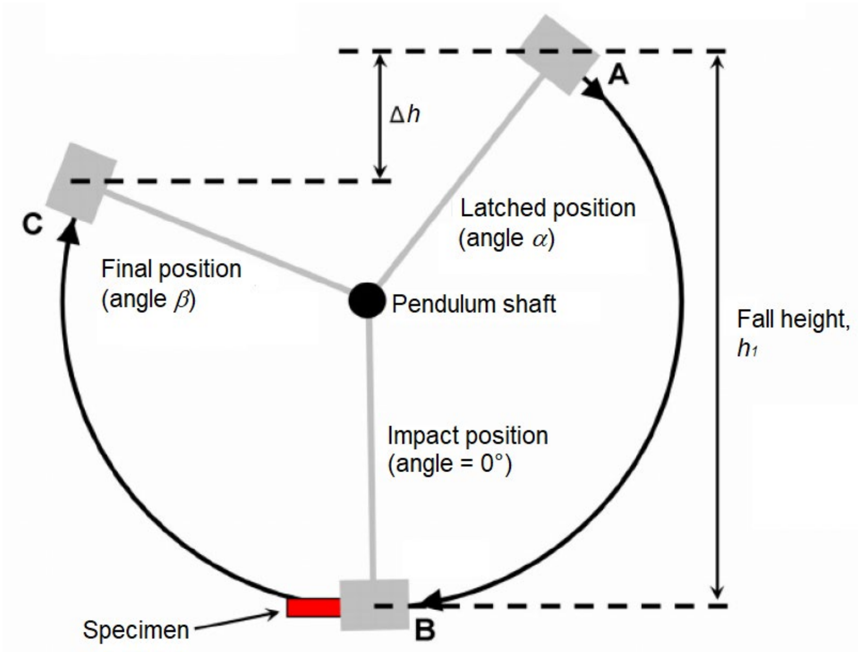

Figure 3 - Schematics of a Charpy pendulum machine.

After breaking the specimen in its path, the hammer rises up to its final position (C in Figure 3), corresponding to the rise angle β. In position C, the potential energy of the hammer (residual energy) is given by:

$$E_{res} = mgh_2 \ , \tag{4}$$

where h_2 is the height to which the hammer rises after breaking the specimen, which can be expressed as:

$$h_2 = L[1 + \sin(\beta - 90°)] \quad . \tag{5}$$

Again, substituting eq. (5) into eq. (4), we obtain:

$$E_{res} = mgL[\sin(\beta - 90°)] \ . \tag{6}$$

The spent, or uncorrected, fracture energy, E_{spent}, is given by the difference between potential energy and residual energy:

$$E_{spent} = E_{pot} - E_{res} = mgL[\sin(\alpha - 90°) - \sin(\beta - 90°)] \quad . \tag{7}$$

Eq. (7) does not account for energy losses due to windage (air resistance) and friction. These losses are quantified by performing one or more free swings (*i.e.*, dropping the hammer without a specimen in place). According to ASTM E23, losses must not exceed 0.4 % of the machine capacity, or potential energy, E_{pot}.

The energy recorded from the free swing(s) is then normalized by the total swing angle ($\alpha + \beta$), thus obtaining the relative windage & friction coefficient (J/°), RWF, which is used to determine the energy losses corresponding to the total swing angle ($\alpha + \beta$) for an actual test.

As a result, the windage & friction-corrected absorbed energy, KV, is given by:

$$KV = mgL[\sin(\alpha - 90°) - \sin(\beta - 90°)] - RWF(\alpha + \beta) \ . \tag{8}$$

2. *LabVIEW* software for reading digital Charpy machine encoders

During FY2023, a *LabVIEW* program was developed in-house at NIST to directly monitor the angular position of a Charpy pendulum hammer via the output of a digital encoder, and derive the value of absorbed energy from the total swing angle.

As seen in Figure 4, the machine encoder is connected directly with a National Instruments Digital Acquisition (DAQ) board, model USB-6212, which is in turn connected to a laptop computer via the USB port. An external power supply is also present, as the 5 V DC source included in the DAQ board does not provide enough current for the digital encoder.

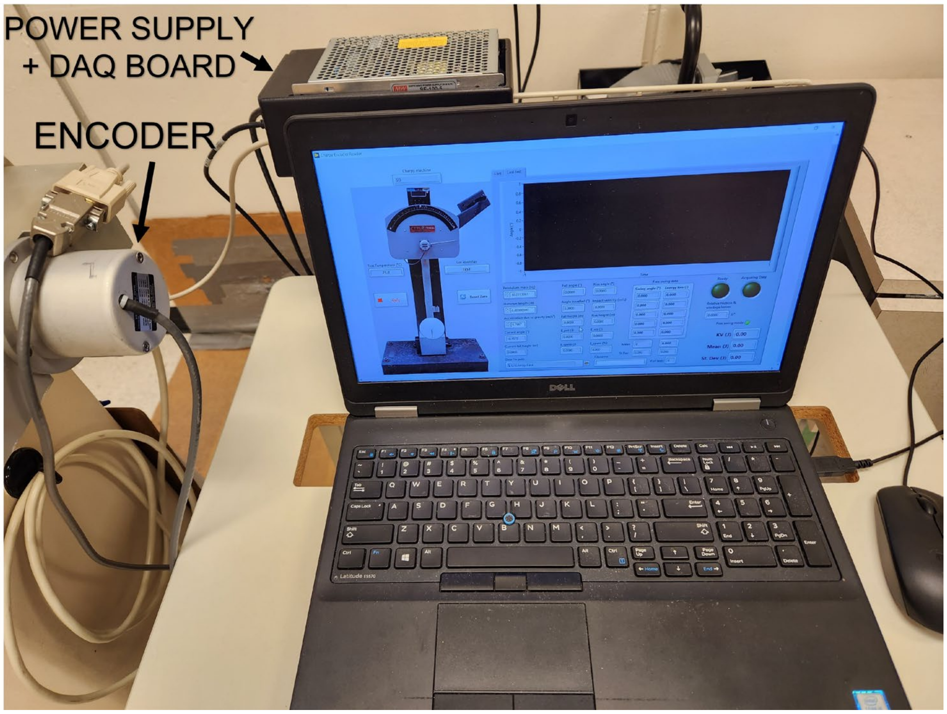

Figure 4 – Connection between digital encoder and acquisition laptop for one of the NIST reference machines.

2.1. User instructions for the "Charpy Encoder Reader" *LabVIEW* code

2.1.1. Machine selection

When the software is started, the window "Select Charpy Machine" (Figure 5) pops up. The machine used is selected from a drop-down list which includes three options, each corresponding to one of the reference machines (SI3, TO2, TK). Once the machine is selected, the characteristic parameters required by eq. (8), *i.e.*, pendulum mass (kg) and hammer length (m), plus the local acceleration of gravity in Boulder, Colorado (9.796 m/s²), are filled in automatically. The user only needs to enter an identifier for the lot/material tested, and the test temperature (the default value is 21 °C, which corresponds to the ambient temperature of the NIST Charpy Laboratory in Boulder).

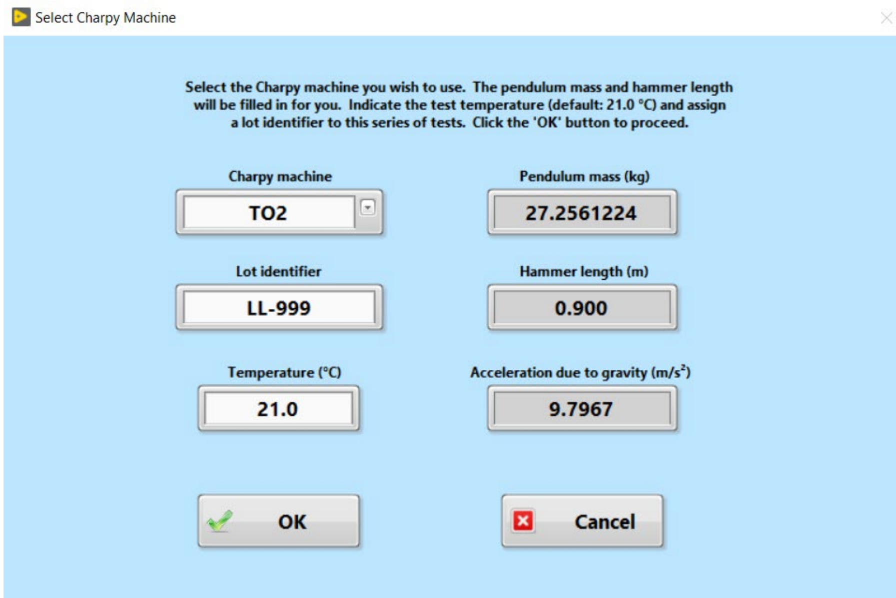

Figure 5 – Charpy machine selection window.

Once the lot/material identifier has been entered, the "OK" button appears. By clicking it, the machine selection window closes, and the user is taken to the main application screen (Figure 6).

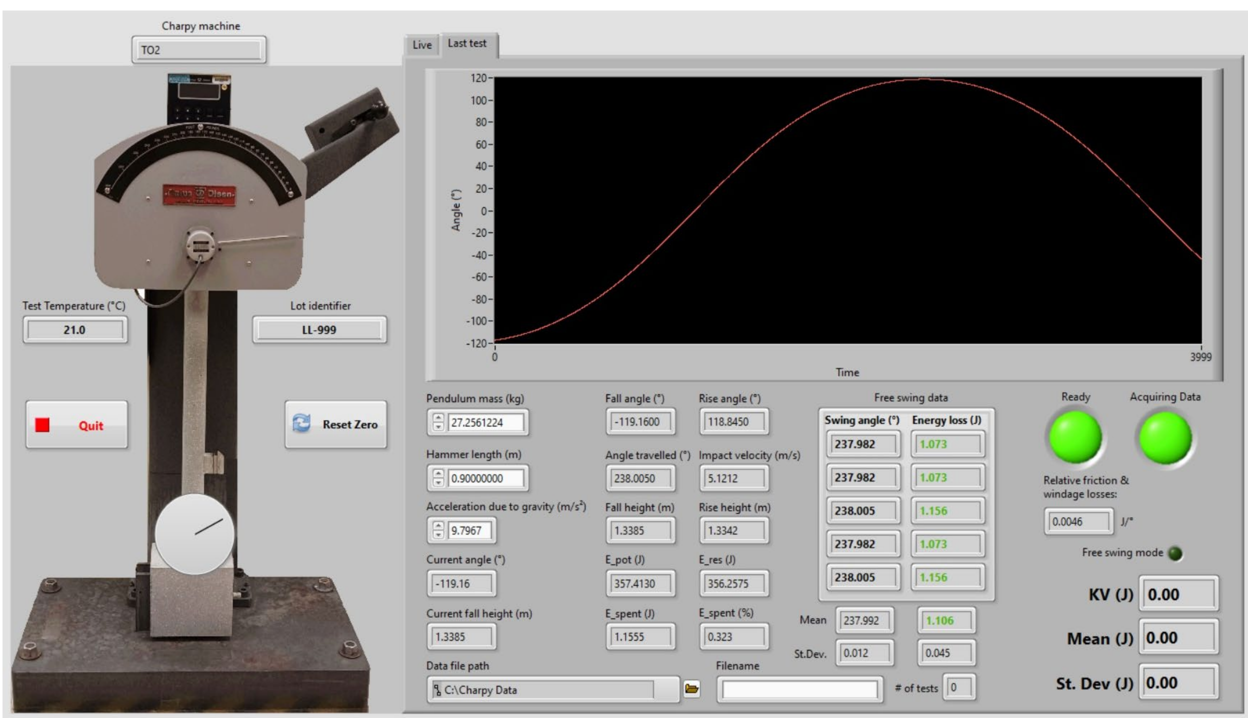

Figure 6 – Main screen of the *LabVIEW* program "Charpy Encoder Reader".

The information entered by the user in the previous window appears in the left portion of the screen, along with a picture of one of the reference machines (TO2).

2.2. Determination of friction & windage losses: free swings

Upon the first appearance of the main screen, the green light at the bottom right of the screen ("Free swing mode") is on (Figure 6). This means that the software is ready to record the total swing angles for five free swings, where the hammer is released from the latched position without a specimen in place.

Before performing the free swings, the position of the hammer corresponding to zero angle must be confirmed by letting the hammer hang steadily in the vertical position and clicking the "Reset Zero" button on the right side of the machine picture. Any value originally displayed in the "Current angle (°)" box will be zeroed.

Before executing the first free swing, the hammer must be lifted and latched. After the hammer is in the latched position for approximately 5 seconds, the software is ready to acquire the first fall and rise angles, or the first (total) swing angle, as indicated by the green "Ready" and "Acquiring Data" lights turning on. The sequence is repeated five times, as the software requires 5 free swings to calculate the mean energy losses due to windage and friction by means of eq. (7). Between each free swing and the next, the user must wait 5 seconds with the pendulum in the latched position for the "Ready" light to turn back on.

The values of total angle ($\alpha + \beta$) and energy loss (KV_{unc}) for each free swing are reported inside the "Free Swing Data" box, while mean values and standard deviations are displayed below the box (Figure 7). If the energy loss for an individual swing is less than 0.4 % of the machine capacity (ASTM E23 requirement), the value is displayed in **green** (valid), otherwise the number appears in **red** (invalid). The same color coding applies to the mean energy loss.

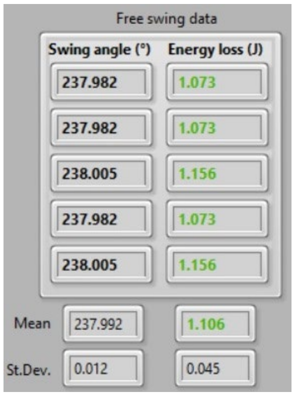

Figure 7 – Information about the five free swings to be performed before the Charpy tests.

2.3. Charpy impact tests

Once friction and losses have been determined upon completion of the fifth free swing, the "Free swing mode" light turns off. With the hammer in the latched position for more than 5 s and ready to be released, the system is ready to acquire encoder information for the actual Charpy tests, as indicated by the green "Ready" and "Acquiring Data" lights turning on.

The machine characteristics used in the absorbed energy calculations (pendulum mass, hammer length, and acceleration of gravity) are shown in the left portion of the "Live Impact" window. The test information displayed in the central portion (Figure 6) includes:

- Fall angle, α (°).
- Rise angle, β (°).

- Angle travelled, $\alpha+\beta$ (°).
- Impact velocity, v_0 (m/s), given by:

$$v_0 = \sqrt{2gh_0} \quad , \tag{9}$$

  where h_0 is the fall height (m), and eq. (9) is derived from the equality between potential energy at hammer release and kinetic energy at impact ($mgh_0 = \frac{1}{2}mv_0^2$).
- Rise height corresponding to the angle β (m).
- Potential energy, E_{pot} (J), corresponding to the machine capacity.
- Residual energy, E_{res} (J), given by eq. (6).
- Spent energy, E_{spent} (J), corresponding to the difference between machine capacity and residual energy, eq. (7); this coincides with the absorbed energy, not corrected for windage and friction.
- Percent spent energy, E_{spent} (%).

At the bottom, information about the output file should be entered: data file path (a default path is displayed) and the filename. The user is prompted to enter a filename after the first impact test, unless the information has already been provided.

Note that, if the file already exists, information about the free swings and the additional test results is appended to the existing file contents.

In the right bottom portion of the "Last Impact" window, the following is displayed:

- Absorbed energy, KV (J). The value is shown in **green** if it corresponds to 80 % or less than E_{pot}, in **red** if KV > 80 %.[1]
- Average absorbed energy for all the tests performed.
- Standard deviation of the absorbed energies for all the tests performed.

The last two quantities, and specifically the standard deviation, can be useful to assess the likelihood that a lot of reference Charpy specimens can be successfully certified.

2.4. "Live" window

By clicking the tab "Live" at the top of the screen, the window shown in Figure 8 is displayed. Two plots are shown, both visualizing the current (instantaneous) angle with two different time/sampling scales.

Above the upper plot, the values of the current angle (left) and the start angle (right) are displayed. Below the lower plot, the value of the threshold angle is shown. As explained in the adjacent caption, if the angle of the hammer remains above this threshold value longer than approximately 5 seconds, the system becomes armed and ready for acquisition, and both the green lights "Ready" and "Acquiring Data" in the "Last Impact" window come on.

[1] According to ASTM E23, absorbed energy values above 80 % of the machine capacity are inaccurate, as the underlying hypothesis of substantially constant velocity during the impact test is grossly violated.

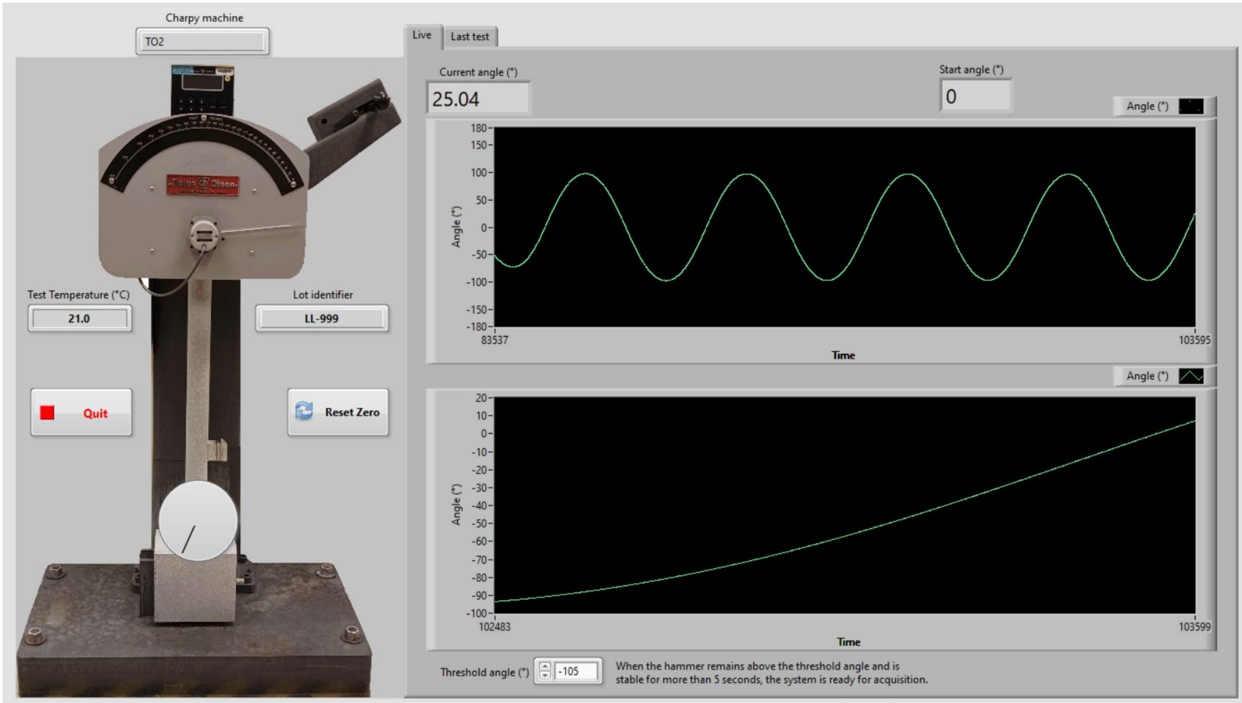

Figure 8 - "Live" window for the visualization of the instantaneous encoder angle.

2.5. Output (results) file

An example of output file generated by the *LabVIEW* code is provided in Appendix A. The file is in ASCII (.txt) format with TAB delimiters, which can be easily converted to spreadsheet format, where data will become neatly organized in columns.

The file header contains information about the selected Charpy machine, its characteristic parameters (hammer mass and length), the local acceleration of gravity, as well as information entered by the user before running the tests (test temperature and lot id). The final items in the header are the results of the free swings (average percent energy loss[2] and relative friction and windage losses).

The results section contains the following information for each of the tests performed:

- fall angle (°)
- fall height (m)
- potential energy (J)
- impact velocity (m/s)
- rise angle (°)
- rise height (m)
- residual energy (J)
- energy spent (J).

In case a series of tests on the same material/lot etc. is split in multiple sessions or days, and provided the user specifies an existing path and filename, the new test results are appended to the previous ones, following a new header section (the determination of windage and friction

[2] With respect to the machine capacity.

through free swings has to be repeated when a test series is resumed). And example of this is shown in Appendix A.

3. Validation of the absorbed energy results provided by the *LabVIEW* software

To confirm the reliability of the encoder angle measurements provided by the newly developed *LabVIEW* code, and the accuracy of the calculations of absorbed energy, a number of Charpy tests on previously certified lots of three energy levels (low, high, and super-high) were conducted on each of the NIST reference machines, half using the old acquisition system (T-O encoder boxes) and half using the new system shown in Figure 4, including the "Charpy Encoder Reader" software. The detailed test matrix is shown in Table 1. All tests were performed at room temperature (21 °C ± 1 °C), and the number of specimens tested corresponded to the number of samples available on storage.

Table 1 - Test matrix for the validation of the "Charpy Encoder Reader" software.

Charpy machine	Acquisition system	Energy level		
		Low	High	Super-High
SI3	T-O box	8	11	9
	LabVIEW	7	11	9
TO2	T-O box	8	14	9
	LabVIEW	8	14	9
TK	T-O box	5	12	10
	LabVIEW	5	13	9

3.1. SI3 machine

Specimens from LL-190 (low-energy), HH-178 (high-energy), and SH-66 (super-high energy) were tested on the SI3 machine. The results are shown in Table 2, along with average values, standard deviations (SD), and coefficients of variation, CV (given by the standard deviation divided by the average value).

Table 2 - Absorbed energy values (J) obtained on the SI3 reference machine.

	LL-190		HH-178		SH-66	
	T-O Box	*LabVIEW*	T-O Box	*LabVIEW*	T-O Box	*LabVIEW*
	18.33	18.08	103.21	105.47	200.33	185.99
	18.05	19.01	107.70	98.57	197.27	188.94
	18.84	18.08	101.25	101.33	188.54	185.59
	18.69	19.74	99.91	105.90	187.71	184.22
	19.12	19.45	103.03	103.75	183.79	183.57
	18.33	19.88	104.74	104.91	189.38	190.55
	18.12	20.45	104.47	100.53	181.28	191.23
		20.09	103.84	104.73	188.45	183.70
			102.5	106.7	181.93	186.09
			103.03	104.19		
			101.33	100.17		
Mean	18.50	19.35	103.18	103.15	188.74	186.48
SD	0.40	0.89	2.08	2.67	6.47	2.73
CV	2.1%	4.6%	2.0%	2.6%	3.4%	1.5%

3.2. TO2 machine

Specimens from LL-199 (low-energy), HH-173 (high-energy), and SH-60 (super-high energy) were tested on the TO2 machine. The results are shown in Table 3.

Table 3 - Absorbed energy values (J) obtained on the TO2 reference machine.

	LL-199		HH-173		SH-60	
	T-O Box	*LabVIEW*	T-O Box	*LabVIEW*	T-O Box	*LabVIEW*
	19.97	20.34	135.50	126.05	193.72	185.69
	19.36	19.74	132.85	130.96	184.41	191.75
	19.71	18.55	134.83	129.63	192.10	190.07
	19.79	19.25	126.80	128.41	190.21	190.16
	19.71	18.47	124.71	129.06	193.00	194.23
	19.27	19.33	130.58	139.15	191.02	189.03
	19.97	18.73	132.09	130.30	192.55	190.86
	20.40	18.30	134.93	129.07	185.87	195.61
			132.28	128.41	191.02	
			130.58	129.06		
			132.57	126.61		
			131.62	131.42		
			130.30	131.70		
			132.57	133.50		
Mean	19.77	19.09	131.59	130.24	190.43	190.93
SD	0.36	0.71	2.98	3.23	3.21	3.07
CV	1.8%	3.7%	2.3%	2.5%	1.7%	1.6%

3.3. TK machine

Specimens from LL-187 (low-energy), HH-185 (high-energy), and SH-65 (super-high energy) were tested on the TK machine. The results are shown in Table 4.

Table 4 - Absorbed energy values (J) obtained on the TK reference machine.

	LL-187		HH-185		SH-65	
	T-O Box	*LabVIEW*	T-O Box	*LabVIEW*	T-O Box	*LabVIEW*
	16.88	16.35	117.90	107.77	196.07	186.17
	16.48	16.75	105.21	116.29	192.90	186.08
	17.69	16.65	105.84	106.30	195.40	184.03
	17.18	17.05	108.75	110.78	202.24	188.89
	16.78	16.65	109.79	113.28	190.78	185.88
			110.00	105.57	182.72	185.88
			114.99	114.84	180.27	187.24
			113.64	113.07	183.11	180.60
			115.10	109.63	179.69	180.90
			110.11	111.92	179.29	
			108.65	108.28		
			110.31	109.84		
Mean	17.00	16.69	110.86	110.63	188.25	185.07
SD	0.46	0.25	3.83	3.36	8.23	2.77
CV	2.7%	1.5%	3.5%	3.0%	4.4%	1.5%

3.4. Statistical analyses

Absorbed energy values obtained for each combination of specimen lot, Charpy machine, and acquisition system (T-O Box or *LabVIEW* software) were statistically analyzed to establish the significance of the recorded differences. The following steps were undertaken[3]:

- The variances of the two data sets (T-O Box or *LabVIEW*) were analyzed by *Two-Sample F-Tests for Variances*, which test the null hypothesis that two normally distributed populations have the same variance [3]. If the resulting probability p is greater than the confidence level α (normally 0.05), differences between the variances can be neglected.
- The mean absorbed energy values of the two data sets corresponding to T-O Box and *LabVIEW* were examined using *Two-Sample t-tests Assuming Equal Variance* (if $p > 0.05$ in the previous step) or *Assuming Unequal Variance* (if $p \leq 0.05$ in the previous step) [3]. Again, using a confidence level $\alpha = 0.05$, if $p > 0.05$ the means are not statistically different.

The results obtained for all the lot/machine/system combinations considered are summarized in Table 5.

For most of the statistical tests performed (12 out of 18, or 67 %), statistically significant differences have not been observed. More specifically, as far as mean absorbed energies are concerned, differences were found not statistically significant in 7 out of 9 cases, or 78 %. The two lots for which significant differences were observed were both low-energy (LL-190 and LL-

[3] Both the *F*-test and the *t*-test assume that the samples are normally distributed. This is a reasonable assumption in the case of Charpy tests for reference (certified) specimen lots.

199) and yielded *p* values relatively close to 0.05 (0.035 in both cases).

Table 5 - Summary of the statistical analyses (*F*-tests and *t*-tests) performed.

Test machine	Lot	Acquisition system	Mean (J)	SD (J)	*p*	Variances are…	*p*	Means are…
SI3	LL-190	T-O Box *LabVIEW*	18.50 19.35	0.40 0.89	0.033	**Different**	0.035	**Different**
	HH-178	T-O Box *LabVIEW*	103.18 103.15	2.08 2.67	0.216	**Not different**	0.913	**Not different**
	SH-66	T-O Box *LabVIEW*	188.74 186.48	6.47 2.73	0.018	**Different**	0.883	**Not different**
TO2	LL-199	T-O Box *LabVIEW*	19.77 19.09	0.36 0.71	0.047	**Different**	0.035	**Different**
	HH-173	T-O Box *LabVIEW*	131.59 130.24	2.98 3.23	0.384	**Not different**	0.261	**Not different**
	SH-60	T-O Box *LabVIEW*	190.43 190.93	3.21 3.07	0.458	**Not different**	0.752	**Not different**
TK	LL-187	T-O Box *LabVIEW*	17.00 16.69	0.46 0.25	0.136	**Not different**	0.217	**Not different**
	HH-185	T-O Box *LabVIEW*	110.86 110.63	3.83 3.36	0.335	**Not different**	0.879	**Not different**
	SH-65	T-O Box *LabVIEW*	188.25 185.07	8.23 2.77	0.003	**Different**	0.275	**Not different**

Overall, the tests performed confirmed the equivalence between the two acquisition systems and support the decision to use the *LabVIEW* software in the future (the T-O Boxes will be kept as a backup system).

4. Conclusions

A new acquisition system has been developed at NIST for monitoring angles yielded by the digital encoders of the three Charpy reference machines in Boulder, Colorado. The system is operated by newly developed *LabVIEW* software, which provides the conversion between encoder angles and absorbed energies. This will replace the system used at NIST in the past 30 years, consisting of Tinius-Olsen (T-O) Encoder Boxes connected to the machine encoders.

Impact tests on specimens from several certified NIST reference lots were performed on each reference machine using both the T-O Boxes and the new acquisition system. The results were statistically compared to assess the significance of the observed differences.

The two systems were found to be substantially equivalent, and the new acquisition system, based on the *LabVIEW* code, will be used in the certification of future NIST indirect verification specimens.

References

[1] ASTM E23-23a, *Standard Test Methods for Notched Impact Testing of Metallic Materials*, ASTM International, West Conshohocken, PA.

[2] ISO 148-2:2016, *Metallic materials — Charpy pendulum impact test — Part 2: Verification of testing machines*, International Standards Organization, Geneva, Switzerland.

[3] G. W. Snedecor and W. G. Cochran, *Statistical Methods*, Eight Edition, 1983, Iowa State University Press.

Appendix A. Example of output (results) file

```
Machine ID:  TO2
Pendulum Mass, m =  27.25612245   kg
Hammer Length, L =  0.90000      m
Local acceleration of gravity, g =      9.7967 m/s²
Test Temperature =  21.0   °C
Lot Identifier:     test
Average Percent Energy Loss:     0.32   %
Relative Friction & Windage Losses:     0.0048 J/° (angle)


Fall Angle a, °     Fall Height h, m    Potential Energy, J Impact Velocity, m/s
       Rise Angle b, °     Rise Height h1, m   Residual Energy, J  Energy Spent, J
       KV (J)
-119.160     1.339  357.41 5.121  93.870 0.961  256.54 100.88 99.86
-119.160     1.339  357.41 5.121  94.207 0.966  257.95 99.46  98.44


Machine ID:  TO2
Pendulum Mass, m =  27.25612245   kg
Hammer Length, L =  0.90000      m
Local acceleration of gravity, g =      9.7967 m/s²
Test Temperature =  21.0   °C
Lot Identifier:     test2
Average Percent Energy Loss:     0.28   %
Relative Friction & Windage Losses:     0.0042 J/° (angle)


Fall Angle a, °     Fall Height h, m    Potential Energy, J Impact Velocity, m/s
       Rise Angle b, °     Rise Height h1, m   Residual Energy, J  Energy Spent, J
       KV (J)
-119.137     1.338  357.33 5.121  92.722 0.943  251.73 105.60 104.72
-119.115     1.338  357.25 5.120  93.442 0.954  254.75 102.50 101.62
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