NIST Technical Note 2081

Investigations on SI-Traceable Dynamic Calibration of Instrumented Charpy Strikers – Activities Performed at NIST in FY2019

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https://doi.org/10.6028/NIST.TN.2081

National Institute of
Standards and Technology
U.S. Department of Commerce

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Investigations on SI-Traceable Dynamic Calibration of Instrumented Charpy Strikers – Activities Performed at NIST in FY2019

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https://doi.org/10.6028/NIST.TN.2081

January 2020

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

National Institute of Standards and Technology Technical Note 2081
Natl. Inst. Stand. Technol. Tech. Note 2081, 23 pages (January 2020)
CODEN: NTNOEF

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2081

Abstract

In recent years, investigations have been conducted at NIST (as a collaboration between the Fatigue and Fracture Group in Boulder, CO and the Mass and Force Group in Gaithersburg, MD) toward an SI-traceable dynamic calibration of instrumented Charpy strikers. Although Charpy tests are few-millisecond-duration events in which dynamic phenomena are often clearly present, the force measurements from instrumented Charpy tests are predominantly obtained using static calibrations, which has long been recognized as a potential source of significant errors. Several approaches to dynamic calibration have been considered for this work, including methods that have previously been implemented at NIST and elsewhere, and methods that are new in the sense that they are not commonly used or incorporated into standards. A key objective of these investigations is that the calibration be traceable to the International System of Units.

A summary of the activities conducted between January and December 2017 was published as NIST TN 1991, issued in May 2018 with the title "Investigations on SI-Traceable Dynamic Calibration of Instrumented Charpy Strikers," authors: A. Chijoke, N. Vlaijc, E. Mulhern, and E. Lucon. Investigations aimed at optimizing the design of an instrumented Charpy striker were summarized in a paper titled "Design Considerations to Optimize Charpy Instrumented Strikers" (authors: N. Vlaijc, A. Chijoke, and E. Lucon). The paper was submitted in 2018 but has not yet been published at the time of writing, being still in review. The activities and accomplishments of this project during FY2019 are described in this Technical Note.

Key words

Dynamic calibration; instrumented Charpy striker; International System of Units (SI), SI traceability; static calibration.

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Figure 12. Simulated frequency response of initial redesign of U-shaped instrumented striker for the TO3 Charpy machine.

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Figure 14. Drawing of new instrumented striker design for the TO3 machine.

1. Introduction

The Charpy impact test is an experimental test used worldwide since the early 1900s for characterizing the notch toughness of metals, and thereby their suitability for applications ranging from ship hulls and railroad tracks to nuclear reactor pressure vessels. A standard Charpy test consists of a swinging mass (pendulum) dropping from a known height and striking a notched specimen located in its path; the specimen fractures, and the difference between the height to which the pendulum rises and its original height provides a measurement of the energy absorbed in breaking the specimen. The Charpy verification program at the National Institute of Standards and Technology (NIST) supplies thousands of customers worldwide with verification steel specimens that have been certified on the three NIST reference Charpy machines; this program achieves the tightest consistency of any population of Charpy machines in the world [1]. A schematic drawing of a Charpy machine, which identifies its different parts and shows a specimen being impacted, is provided in Fig. 1.

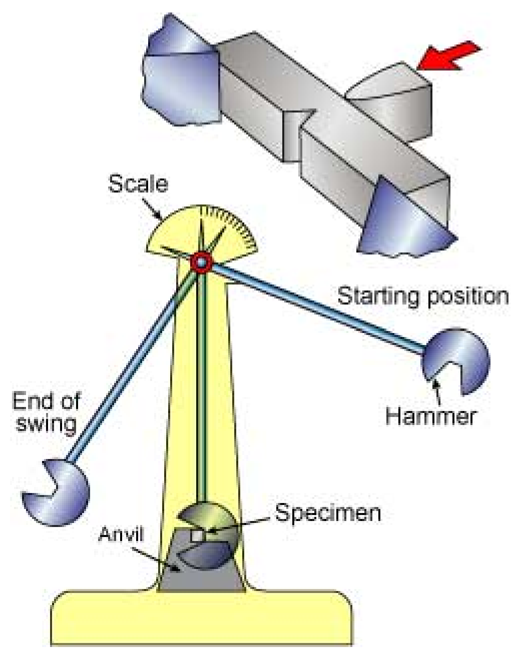

Figure 2. Schematic drawing of a Charpy machine and a Charpy specimen being tested (image reproduced and modified from https://images.app.goo.gl/yBTp4peERVyfo3se8).

In the instrumented version of the Charpy test, strain gauges attached to the striker[1] transform it into a force transducer that provides an indication of the force applied to the specimen during impact (Fig. 2). The force-time record derived from an instrumented Charpy striker offers additional information about the tested material's properties in comparison to a standard (*i.e.*, non-instrumented) impact test. However, impact tests are highly dynamic events, with a duration ranging from 0.1 ms to 5 ms, with force pulse amplitudes typically exceeding 25 kN for steel specimens. Obtaining an accurate SI-traceable dynamic calibration for an instrumented Charpy striker has remained elusive. Currently, instrumented impact

[1] In a Charpy machine, the striker is the part of the swinging hammer that impacts the specimen and, in the instrumented version of the test, is equipped with strain gauges to measure the deformation during the impact.

tests are analyzed based on a static calibration of the instrumented striker. Transforming voltage-time data into force-time data by means of a static calibration is not expected in general to deliver high accuracy, as the sensitivity of the instrumented striker (*i.e.*, the response of the strain gauges) mounted in the Charpy machine will exhibit some degree of dependence on excitation rate (e.g. a non-flat frequency response function). For example, resonances in the response that are excited by the impact event will be falsely interpreted as force oscillation[2], if the interpretation is based on a static calibration.

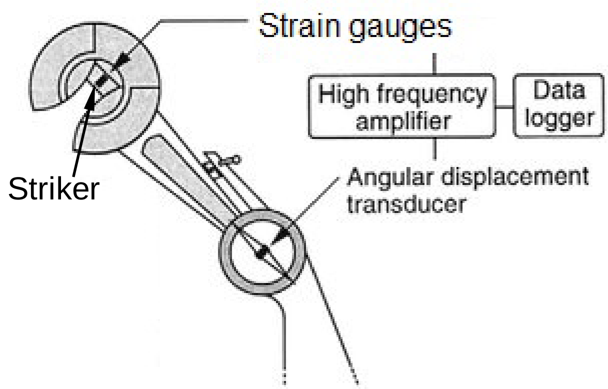

Figure 2. Schematic of an instrumented Charpy test (image reproduced and modified from https://images.app.goo.gl/z57xgdHtNsZWSgfq6).

Some improvement is achieved by correcting the observed force values by equalizing the absorbed energy derived from the pendulum swing angles and the instrumented energy obtained by integrating force with respect to inferred displacement [3]. This approach has been incorporated into the ASTM E2298 standard [4]. However, as shown in Ref. [3] and discussed below, there is room for improvement. An alternative approach, which aims at exploring higher loading rates, consists of inferring the conversion factor between striker signal and force from a purely elastic, low-blow instrumented impact test of an unnotched Charpy specimen [5]. This test allows determining the compliance of an impact machine [6]. Other efforts to perform an actual dynamic calibration (see e.g. [7,8]) have not led to low-absolute-uncertainty force-versus-time data from instrumented Charpy tests. In this Technical Note, we describe our ongoing effort to perform a low-uncertainty, SI-traceable, dynamic force calibration of instrumented Charpy strikers at NIST. Success of this effort would represent a major advance, improving interpretation of instrumented test results and potentially resolving current disagreements between results obtained on different machines and by different institutions.

In general, it is not possible to represent the dynamic sensitivity of a Charpy instrumented striker as a single time-independent function of force. Methods of representing the dynamic sensitivity include the frequency response function (frequency domain) or the impulse response function (time domain), which assume linearity and time-invariance[3] of the striker response. Provided that these conditions are satisfied, such a calibration provides the sensitivity to any applied force trace. Determining such a dynamic sensitivity from a calibration requires the application of a known and/or sufficiently fast dynamic force to the

[2] Note that resonances in the striker and sample response can lead to oscillation of the force during impact, as shown in Ref [2]; however, the amplitude of force oscillation assigned based on a static calibration is in general not expected to be correct.
[3] This is not to be confused with time-independence. Time-*invariance* means that the *properties of the system* are not changing in time.

striker. Using the determined dynamic sensitivity function to convert the voltage-time trace obtained in breaking a specimen into a force-time trace is an inverse problem, and in general will require regularization in order to provide a useful result [9].

For the dynamically calibrated instrumented striker to provide force values of greatest utility, it is important that the calibration, as well as the subsequent use of the calibration to interpret test results, be traceable. Metrological traceability requires an unbroken chain of calibrations to specified references, and allows measurement results to be reported in units of an agreed reference with quantified uncertainties. It is formally defined as the "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty" [10]. SI-traceability means that the reference is the SI-defining fundamental constants. Thus, for the calibration of an instrumented Charpy striker to yield traceable test results in units of Newtons (or any other force unit defined as a fixed number of Newtons):

(a) The force values applied in the calibration of the striker must have a documented chain of evaluation back to SI defining fundamental constants such as h (Planck constant), c (speed of light in vacuum) and $\Delta\nu$ (hyperfine transition frequency of cesium-133), with quantified uncertainties at each step of the chain, giving rise to the final uncertainties of the applied force values during the calibration. The same applies to the measurement of the output signal from the instrumented striker during the calibration. It may be the case that a correction to the dynamic sensitivity of the striker observed under the conditions of its calibration is required in order to get the sensitivity applicable to a given instrumented test; the uncertainty of any such correction must also be included.

(b) The added uncertainty in performing the instrumented Charpy test must be evaluated and incorporated. This includes for example all significant uncertainty contributions that may arise from electronic noise and environmental influences such as vibration, temperature, atmospheric pressure and electrical interference.

Both uncertainty contributions (a) and (b) must be propagated to the final force values obtained from an instrumented Charpy test, a procedure which may be quite involved [11]. We note that it is not necessary that uncertainties from each significant source are individually evaluated, only that the total uncertainty due to them is determined.

It is also important to mention that unlike the static sensitivity, the dynamic sensitivity of the striker may be different when it is mounted in the Charpy machine (*in-situ*) than when it is removed from the machine (*ex-situ*), and may be different for each machine in which the striker is mounted. This is because the dynamic response to an impact is the response of the entire machine structure. The implication is that the instrumented striker should preferably be dynamically calibrated as mounted in the Charpy machine for use.

2. Impact Calibration Exercise using Custom Impactor

Following from the results obtained in FY2017 and FY2018, a customized impactor was developed to perform transfer calibration of instrumented Charpy strikers. The impactor is a specially designed strain-gage force transducer, for applying impact force pulses without any change to its boundary conditions between its calibration and use. The impactor is calibrated by a primary system, and thus functions as a transfer standard. The data acquisition arrangement used for this method is shown in Fig. 3. The impactor was designed to achieve short impact durations, giving a high available calibration bandwidth. This was achieved primarily by making the mass of the impactor small. Two versions of the impactor were constructed – an aluminum impactor with a mass of approximately 50 g and a stainless steel impactor with a mass of approximately 125 g. The two versions provided force pulses of approximately 100 μs and 200 μs duration respectively in impacts against steel, corresponding to force content bandwidths[4] of approximately 25 kHz and 12 kHz respectively. The impactor was provided with an air-bearing guide that provided high repeatability of the impact location, fine adjustability of the impact location, and fine adjustability of the impact angle.

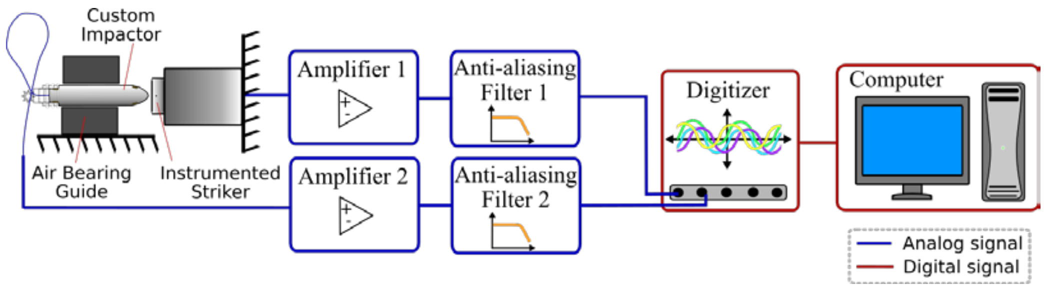

Figure 3. Data acquisition arrangement used for testing the custom impactor method.

These impactors were calibrated in Gaithersburg using the mass impact force standard in Group 684.07 and transported to Boulder for transfer calibration of instrumented Charpy impactors. The mass impact force standard consists of a block of known mass *m*, supported by an air bearing and free to move in one dimension, with its displacement *x(t)* measured by a laser interferometer. A force *F(t)* acting on this block, during an impact upon it by the custom impactor (or any other force transducer under calibration), is determined from the mass and acceleration of the block according to $F(t) = m\, d^2x/dt^2$, with a correction for elastodynamic deformation of the block.

In November 2018, dynamic calibration of instrumented Charpy strikers in the NIST MPM-700 Z-Style Charpy machine was carried out. The aluminum custom impactor was used, due to the shorter pulses (and therefore higher potential calibration bandwidth) that it provided. Analysis of the results revealed a useful calibration bandwidth of approximately 10 kHz, limited primarily by the bandwidth of the NIST mass impact force standard. This is indicated by the increase in statistical uncertainty above 10 kHz in Fig. 4. While this calibration bandwidth may be adequate for many instrumented Charpy measurements, for some measurements, a higher bandwidth is expected to be necessary.

[4] Defined as the frequency at which the force spectral amplitude is reduced to 10 % of the low-frequency value.

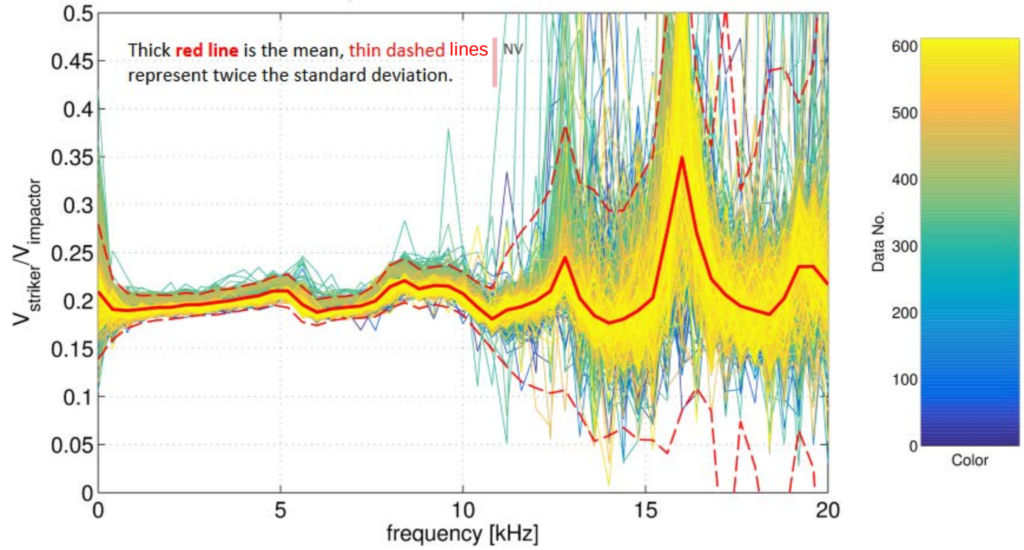

Figure 4. Calibrated transfer frequency response function amplitude of instrumented Charpy striker using custom aluminum impactor, expressed in terms of ratio between striker and impactor voltages, showing statistical contribution to uncertainty.

Analysis of the data gathered during the calibration exercise revealed some inconsistency in the measurements over time, as shown in Fig. 5. We tentatively attribute this to user-related effects occurring with the manually-actuated impactor (e.g. the user remaining in contact with the impactor during its contact with the instrumented striker) or to fragile and fluctuating wiring. We expect that this issue could be solved by improvements to the custom impactor such as mechanized actuation and more-robust wiring.

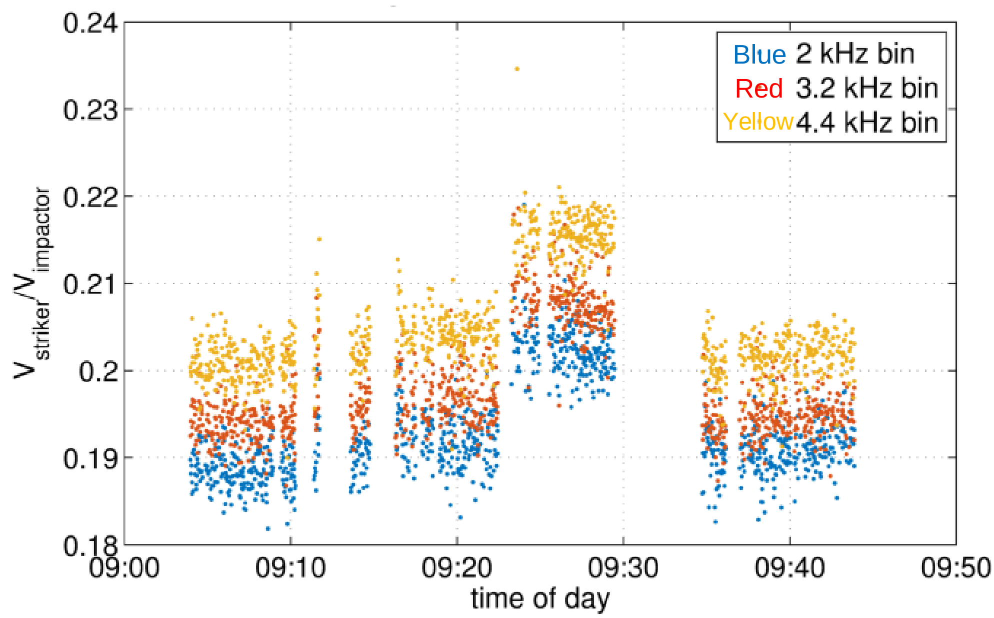

Figure 5. Drift of ratio between impactor and instrumented striker output voltages over the course of 1000 impacts spanning 40 minutes. The change is attributed to variation in the custom impactor response, not the instrumented striker response.

Extending this method to higher calibration bandwidth requires either developing an increased bandwidth of the Gaithersburg mass impact force standard, or obtaining very short (e.g. less than 30 µs) impacts using small impactors ("bullets"). The latter approach would either have small impact forces, increasing the signal-to-noise and linearity requirements, or high impact velocities, increasing the engineering requirement.

3. Development of Ceramic-Specimen Fracture Calibration

An alternative approach for obtaining very short pulses was proposed and tested. The proposed idea was to find or develop Charpy test specimens that would fracture in the required very short times - much shorter than the instrumented Charpy force-time traces to which the calibration would apply. A major advantage of this approach is that the calibration experiment would be simple for users of Charpy machines to carry out, not requiring any calibrated instrument or special apparatus, but only a specimen similar to the specimens used in a standard Charpy test. In this approach, the force amplitude used to fracture the specimen is not measured or known; however, the time duration of the force is determined (bounded). For sufficiently short durations the response of the striker is close to the true impulse response of the striker.

A number of different types of specimens were tested, including deeply-notched and reduced-height brittle metallic Charpy specimens, notched and un-notched macor (ceramic) specimens of 6.35 mm and 12.7 mm square cross sections, and un-notched single-crystal sapphire specimens of 10 mm square cross-section.

To prove the technique, the electrical circuit shown in Fig. 6(a) was assembled, in which the rapid-fracture specimen formed a mechanical switch. From the observed time traces, it could be ascertained that the duration of the force pulse from initial contact to complete fracture was not larger than approximately 50 µs, as indicated by the electrical voltage step width. The actual fracture duration is lower, because electrical contact between part of the broken specimen and the striker is maintained for some period after fracture and extends the duration of the voltage step (no-contact to no-contact). The shortest voltage steps, of approximately 30 µs total duration, were obtained with 6.35-millimeter-square macor specimens.

The continuity-indicating voltage step, as illustrated in Fig. 6(b), helped to provide confidence in the short duration of the force step. However, the instrumented striker output provides a tighter upper bound on the force pulse duration. The instrumented striker acts as a mechanical filter, in general lengthening the output voltage pulse from the striker beyond the duration of the actual force pulse, but not shortening it. Thus, the time from the initial rise above zero of the striker output voltage and the first subsequent zero crossing of this output voltage (start of intermittent contact regime) establishes an upper bound on the force pulse duration. This was found to be a tighter (shorter) bound on the force pulse duration than the continuity-indicating circuit voltage, for the strikers and specimens tested.

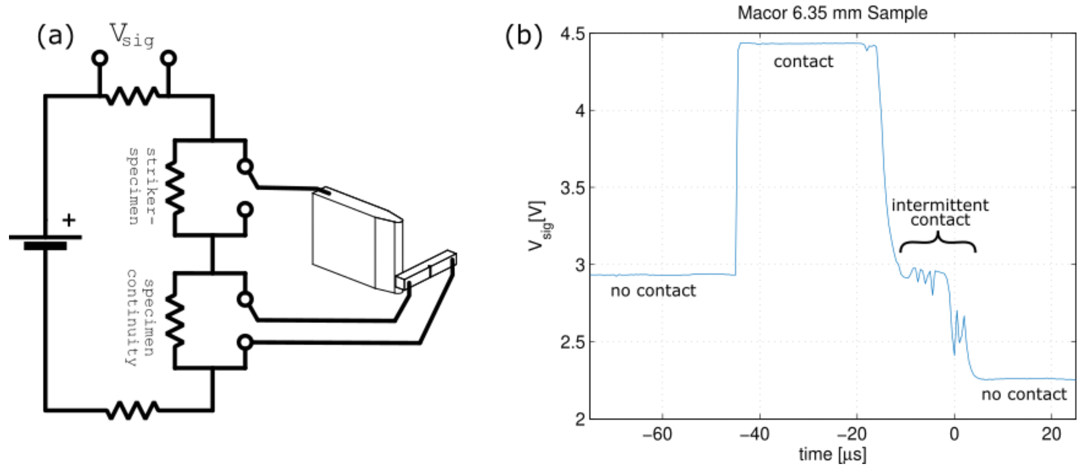

Figure 6. (a) Continuity-indicating electrical circuit incorporating rapid-fracture specimen (b) Continuity-indicating voltage step, establishing an upper bound on the force step width. In the final two portions of the trace (intermittent contact, no contact), the specimen continuity has been broken.

After initial tests of the method in Gaithersburg using a mock Charpy machine with an instrumented striker from the Boulder MPM-700 Z-style machine, a calibration exercise was carried out in Boulder in June 2019 using the developed method. Minimum force pulse durations of approximately 25 microseconds were obtained, allowing low-uncertainty calibration up to a bandwidth of 30 kHz[5]. This approach was used to perform a dynamic calibration of two instrumented strikers of the NIST MPM-700 Z-style Charpy machine (Fig. 7), and one instrumented striker in the NIST Tinius-Olsen U-style Charpy machine designated as TO3. Force-time traces for selected specimens tested on the MPM-700 machine equipped with the JS-2 and JS-4 strikers, respectively, are depicted in Fig. 7.

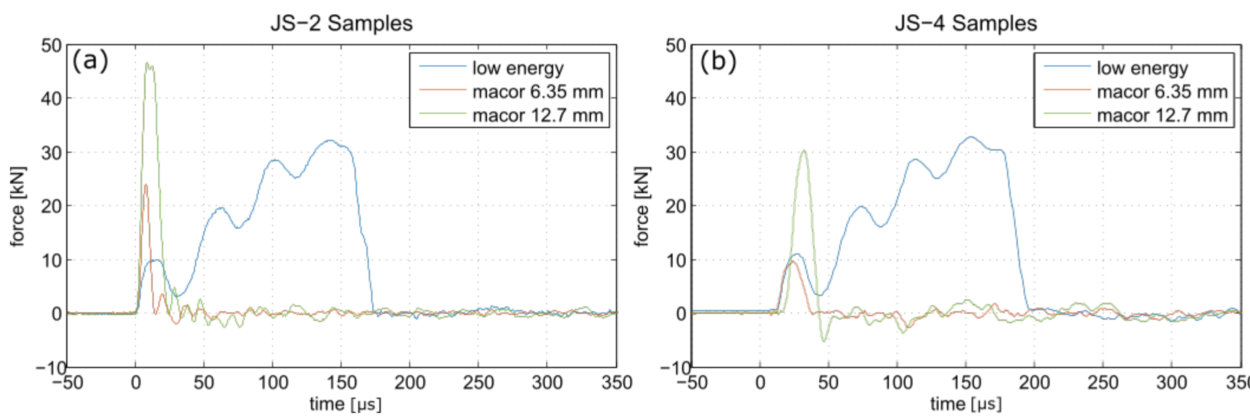

Figure 7. Force-time traces from MPM-700 Z-style machine instrumented strikers: (a) earlier design of striker (JS-2) and (b) more recent design (JS-4).

[5] Defined as the frequency at which the frequency-dependent amplitude uncertainty due to the unknown force duration reaches a value of 20 %. The contribution of this uncertainty component to the relative uncertainty of instrumented Charpy force-time traces is expected to be in general lower, as such time traces are composed of a range of frequencies that are predominantly below this bandwidth limit.

4. Uncertainty of Instrumented Impacts using Calibrated Z-Style Machine

The calibration data collected in the above-described exercise were used to calculate uncertainties in the force-time traces from the fracture of metallic specimens in NIST Charpy machines, such as the ones shown in Fig. 7. The impulse response (to within an overall multiplicative constant) is estimated as the response of the striker to the shortest-duration impact achieved, namely the impact on a 6.35-millimeter-square macor specimens. The estimated impulse response of the JS-2 (MPM-700 Z-style machine), JS-4 (MPM-700 Z-style machine), and JS-1 (Tinius-Olsen U-style machine TO3) strikers are shown in Figs 8, 9, and 10, respectively.

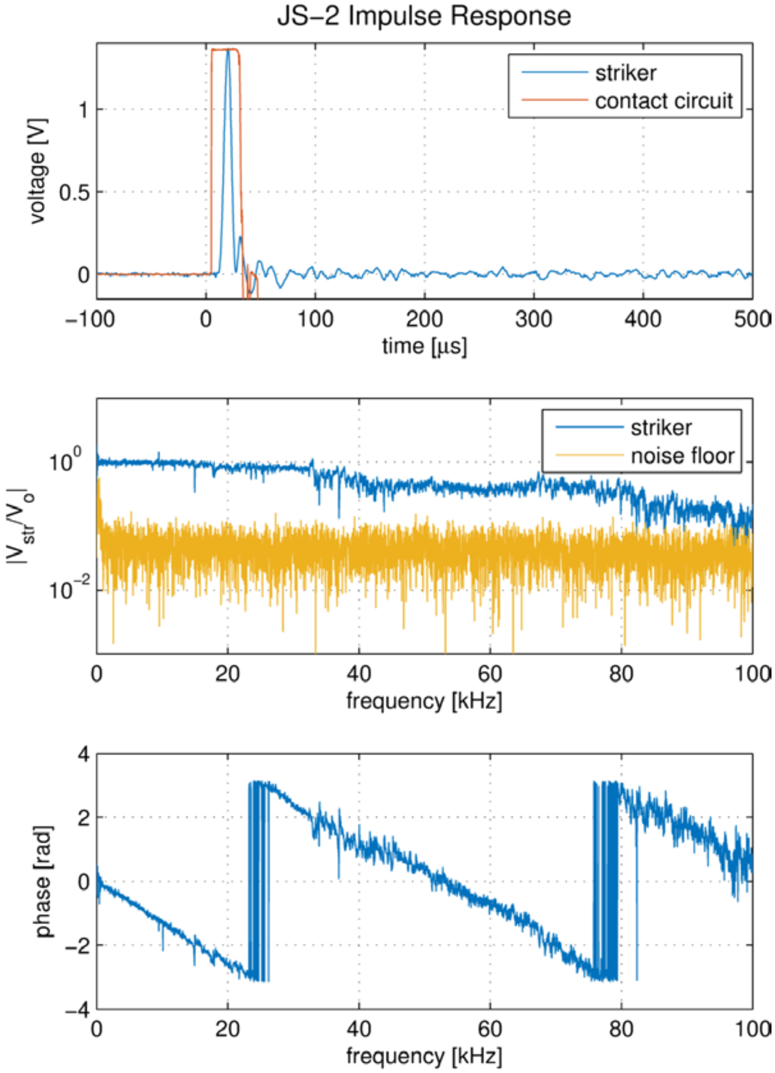

Figure 8. Impulse response of the JS-2 striker in the MPM-700 Z-style machine: (Top) Estimated time-domain impulse response of the striker determined by breaking a 6.35 mm ceramic sample, in units of the output voltage from the instrumented striker output amplifier. (Middle) Frequency-domain representation of the impulse response that is to be scaled by the static sensitivity. (Bottom) Phase response, plotted in the range -π to π (radians). The linear slope of the phase response is not important, reflecting an arbitrary selection of the time = 0 instant.

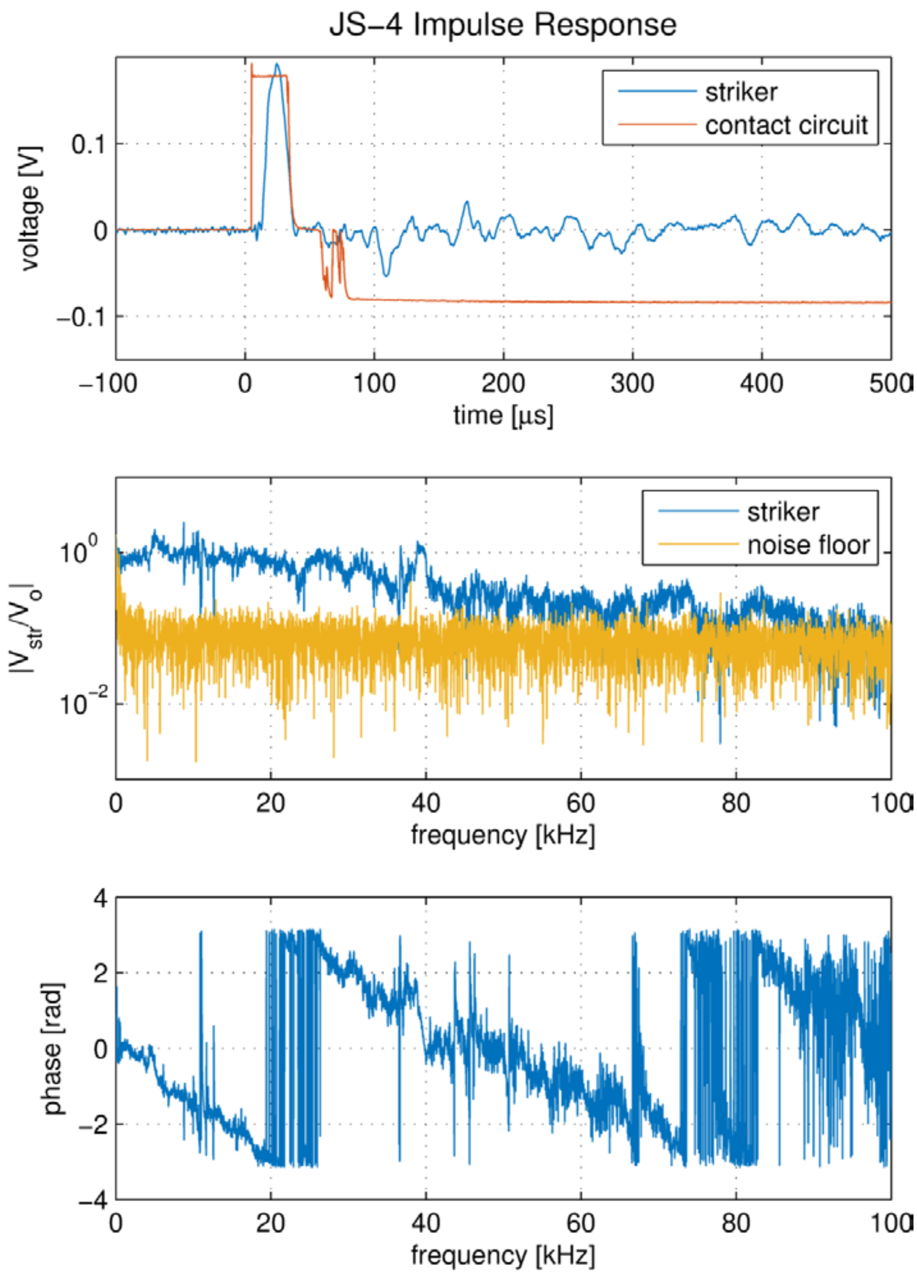

Figure 9. Impulse response of the JS-4 striker in the MPM-700 Z-style machine: (Top) Estimated time-domain impulse response of the striker determined by breaking a 6.35 mm ceramic sample, in units of the output voltage from the instrumented striker output amplifier. (Middle) Frequency-domain representation of the impulse response that is to be scaled by the static sensitivity. (Bottom) Phase response, plotted in the range -π to π (radians). The linear slope of the phase response is unimportant, reflecting an arbitrary selection of the time = 0 instant.

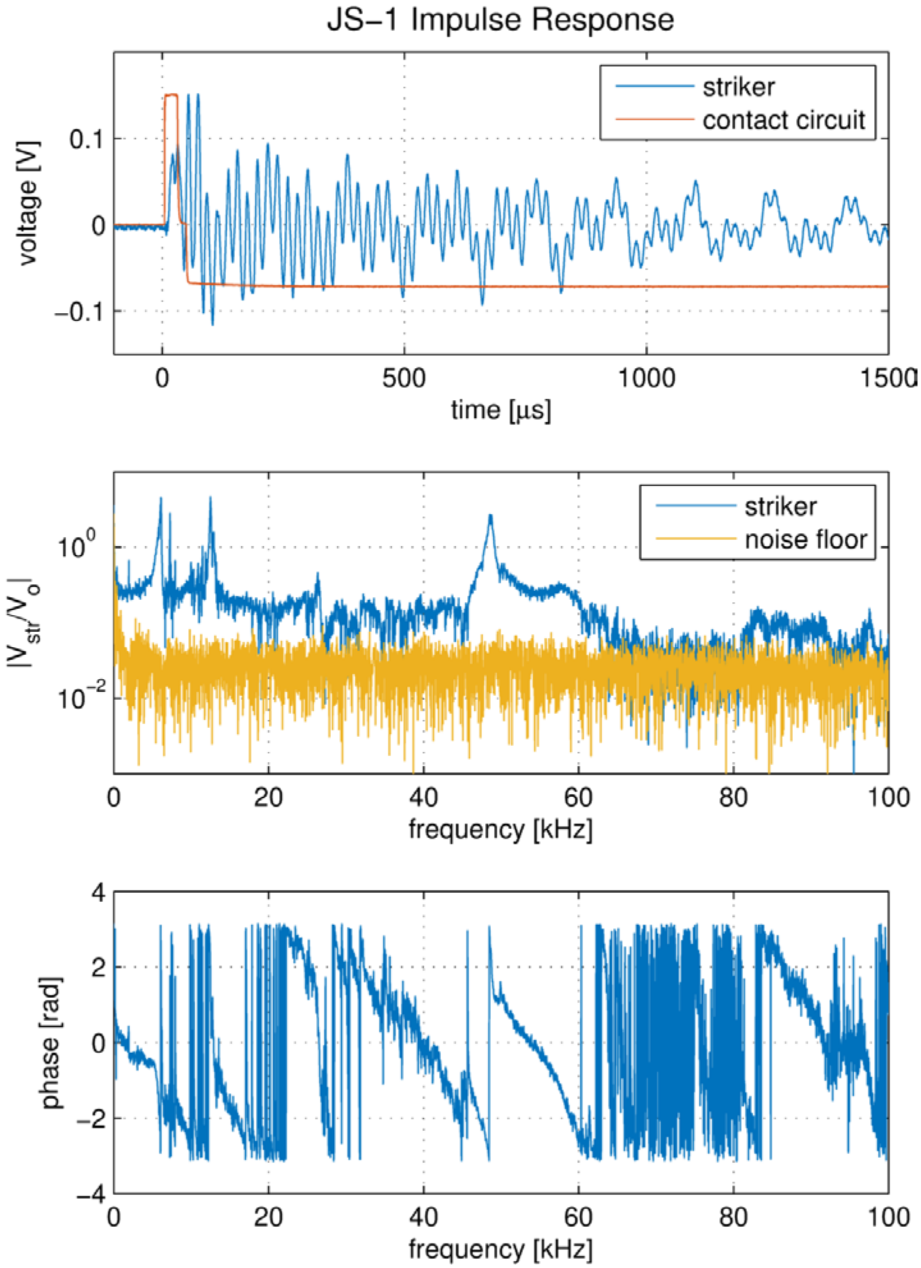

Figure 10. Impulse response of the JS-1 striker in the Tinius-Olsen U-style machine: (Top) Estimated time-domain impulse response of the striker determined by breaking a 6.35 mm ceramic sample, in units of the output voltage from the instrumented striker output amplifier. Note that the striker is still showing a response after the sample has completely fractured. (Middle) Frequency-domain representation of the impulse response that is to be scaled by the static sensitivity. (Bottom) Phase response, plotted in the range -π to π (radians). The linear slope of the phase response is unimportant, reflecting an arbitrary selection of the time = 0 instant.

In each of the figures, the top panel shows the time-domain estimated impulse response function from one impact, the middle panel shows an average of the estimated frequency response function amplitude from 3-4 impacts, and the bottom panel shows an average of the estimated frequency response functions phase from 3-4 impacts. For the JS-1 striker, there is still a strong vibratory response even after 1500 microseconds. Although not shown, the striker's response still has not yet been attenuated to the noise floor after 5 ms. This is also apparent in Fig. 10(b), where there are prominent resonances at approximately 6 kHz and 12 kHz. These resonances are disadvantageous for obtaining low uncertainties up to high bandwidths. These results serve as motivation to redesign the JS-1 striker using some of the design principles used to redesign the JS-3 and JS-4 striker.

Fig. 11 shows the preliminary result for the resulting uncertainty on the force-time test record obtained from the JS-2 striker (more details are provided in Appendix 1). Work to complete and cross-check this evaluation is ongoing. Work to evaluate the uncertainty as a function of measurement bandwidth of Charpy impacts with this machine is also ongoing, while in parallel work to increase the striker bandwidth for the U-style Charpy machines is being undertaken as described in the following section.

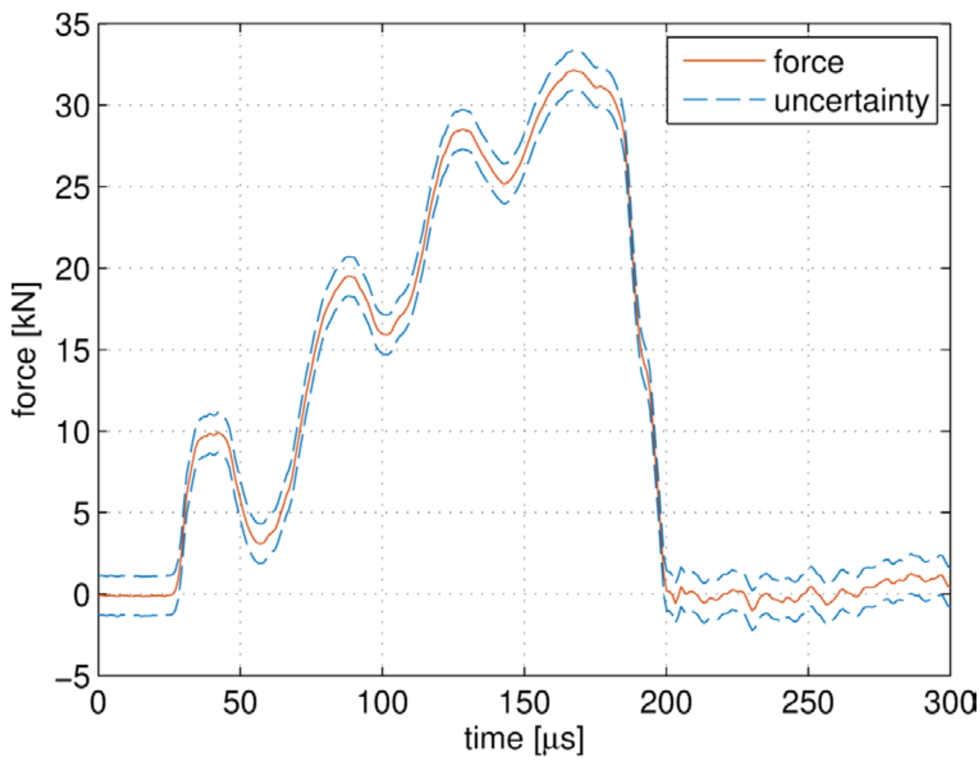

Figure 11. Instrumented Charpy Force-time trace from striker JS-2, with initial evaluation of dynamic uncertainty. The indicated force is based on the static calibration of the instrumented striker, while the uncertainty includes the effects of the deviation of the dynamic sensitivity from the static sensitivity. The uncertainty is provided as a single force value, providing a bound to the force trace at all times after contact, for a stated measurement bandwidth criterion.

5. Redesign of Instrumented Striker for U-Style Machine

In order to reduce the presence of low-frequency dynamics in the U-shaped machines and instrumented strikers, and thereby improve the potential for obtaining low-uncertainty on rapid force variations during Charpy impacts with these machines, a re-design of the striker was carried out. The first step in this was a rapid redesign, porting as much of the design of the custom Z-style machine instrumented strikers developed in FY2018 to the new U-style instrumented striker. Time constraints did not allow extensive finite element simulation to be carried out in this step, in order for procurement and fabrication to move forward. The new striker is being fabricated from a soft near-net blank purchased from Tinius Olsen TMC.

In a second step, a finite element simulation of the striker was carried out, to guide further improvements to its design. Experimentation on various means of increasing the frequency of resonances and antiresonances in the striker response was carried out, within the geometric constraints of the TO3 Charpy machine and the documentary standards governing Charpy testing. Figs 12 and 13 show the increase in the lowest antiresonance frequency from 11 kHz to 15.8 kHz, in going from the design currently being fabricated (initial design) to a new design. This new design employs a multipiece structure with a steel tip and base, and a Beryllium body (at this stage, it is unclear whether it will be alloyed or pure Be). It also provides for damping material to be optionally implanted in the striker to reduce the amplitude of resonant features (such damping material was not included in the simulation used to generate Fig. 12). A version of this striker is being fabricated out of L6 tool steel (Fig. 14), which will allow initial testing of the design before fabrication of the Beryllium version. A monolithic version in L6 tool steel is also being fabricated.

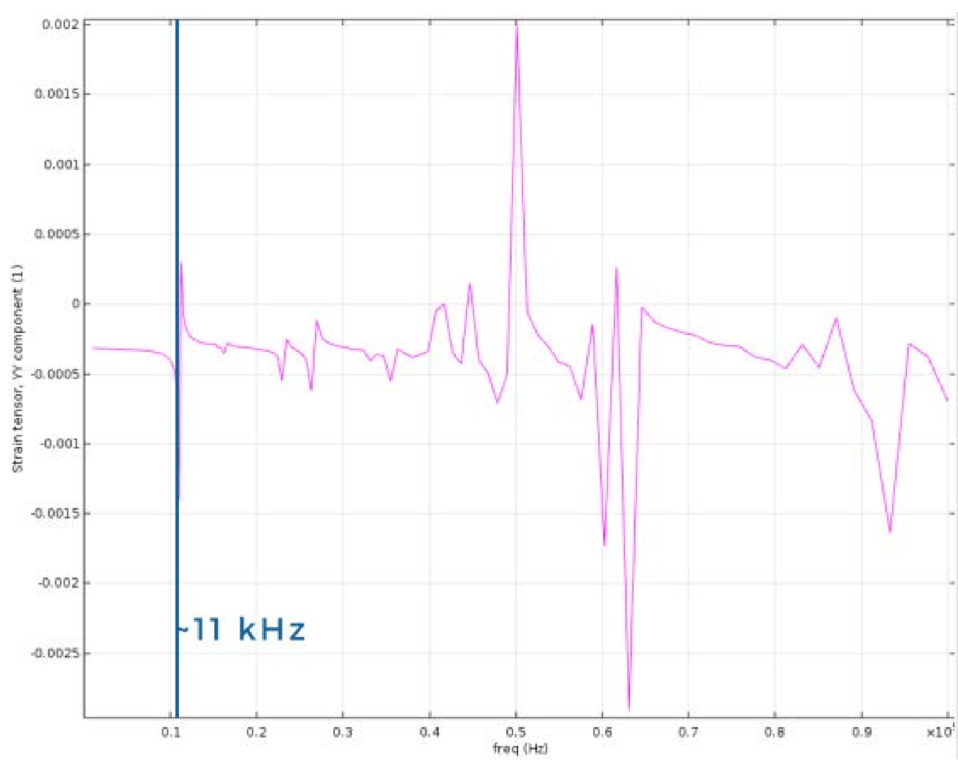

Figure 12. Simulated frequency response of initial redesign of U-shaped instrumer x10^5 iker for the TO3 Charpy machine.

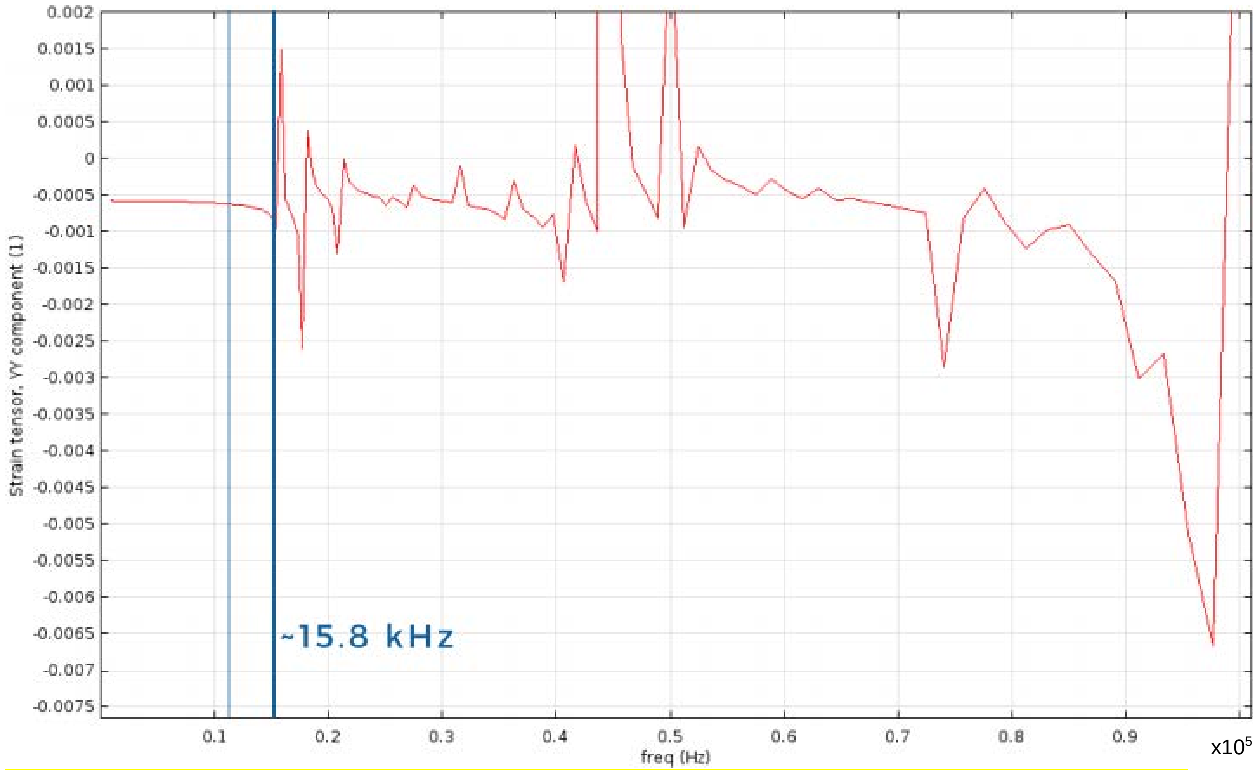

Figure 13. Simulated frequency response of new design of U-shaped instrumented striker for the TO3 Charpy machine.

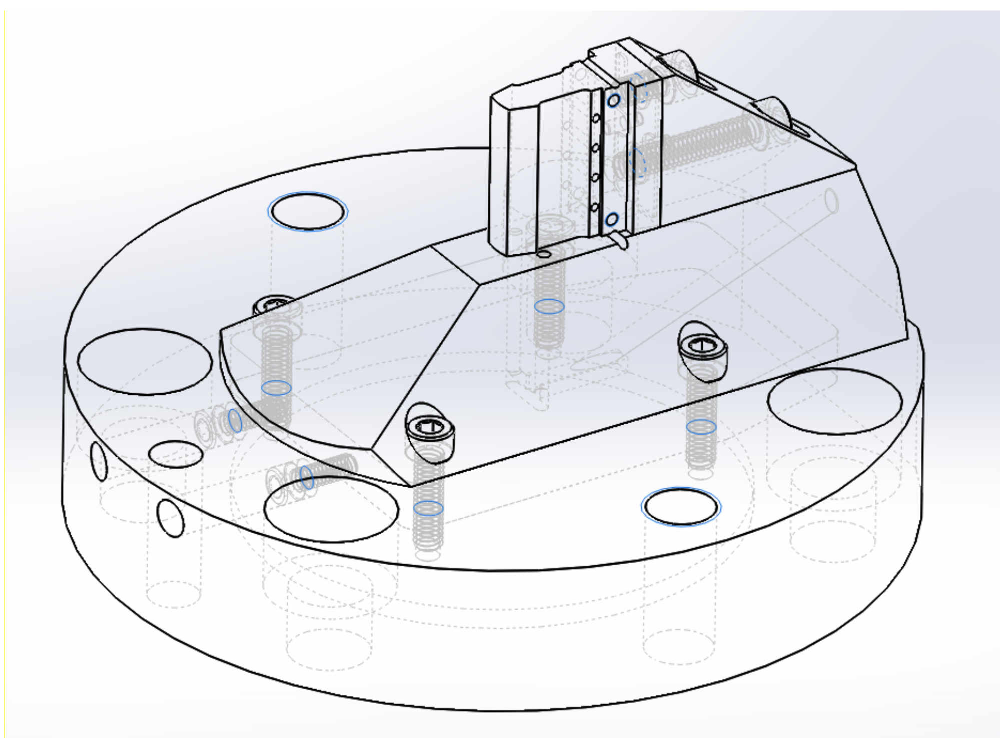

Figure 14. Drawing of new instrumented striker design for the TO3 machine.

6. Conclusions: Achievements and Future Work

The main achievements resulting from the work conducted in FY 2019 can be summarized as follows:

- Design of customized transfer standard impactors that were used to calibrate strikers in the Z-style machine with low uncertainty up to approximately 10 kHz.
- Development of a novel calibration procedure using fast-fracture specimens that has the benefits of low uncertainties to bandwidths of 30 kHz and above, and being easily disseminated to the Charpy testing community. This method was used to calibrate two instrumented strikers in the Z-style machine, and one instrumented striker in the U-style machine.
- For the first time, we have put an uncertainty estimate on the force-time signal obtained in breaking a Charpy specimen (see Figure 10), based on our dynamic calibration.
- Characterization of the performance of a striker in the U-style machine indicating that redesign would likely be of benefit. A new instrumented striker based on a preliminary redesign is under construction and a more refined design has been developed using finite element analysis.

Activities yet to be carried out or concluded include:

- Acquiring data from many repeated ceramic-specimen fractures, to provide data for increased reduction of noise and to give confidence in repeatability of the results.
- Completion of the uncertainty analysis on all the calibrated instrumented strikers.
- Completion of the fabrication and testing of the new instrumented strikers for the Tinius-Olsen U-shaped Charpy machines.
- Dynamic calibration of the new instrumented strikers in the NIST Tinius-Olsen U-shaped Charpy machines.
- Dynamic calibration of the NIST Tokyo-Koki C-shaped Charpy machine.
- Possible design and fabrication of an optimized striker for the NIST Tokyo-Koki C-shaped Charpy machine.

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Appendix 1

Assessment of the uncertainty on the force-time record

We use the static sensitivity and the measured voltage from the striker to indicate the force at any given point in time while breaking the sample. The force at instance n (or equivalently time $t_n = n\Delta t$ for sample time Δt) is:

$$F[n] = \frac{v[n]}{S} \ , \tag{X1}$$

where $F[n]$ is the force, $v[n]$ is the measured voltage, and S is the static sensitivity in units of V/kN. We assume that errors that result in the variations of sampling time Δt are negligible.

The uncertainty on the force $u_F[n]$ at point n indicated by the striker is written as:

$$u_F^2[n] = u_{\text{static}}^2[n] + u_{\text{var}}^2 + u_{\text{dyn}}^2 \ , \tag{X2}$$

where u_{static} is the uncertainty in the static sensitivity of the calibration of the striker, u_{var} is the voltage measurement uncertainty, and u_{dyn} is the regularization uncertainty as a result of using finite bandwidth of the dynamic response function of the system. All the uncertainty components are absolute uncertainties with units of force (kN).

The uncertainty at point n from using the static sensitivity is

$$u_{\text{static}}^2[n] = v^2[n] u_S^2 \ , \tag{X3}$$

where u_S is the absolute uncertainty in the static calibration. The striker was statically calibrated in a material testing machine that was able to apply a compressive force. Accounting for the uncertainty of this machine and the uncertainty due to non-repeatability of a series of calibrations, the relative uncertainty is less than 1 %. It follows that the static calibration uncertainty is then $u_S = (0.01)(6.656 \times 10^{-2} \text{V/kN})$.

The uncertainty u_{var} is the variational or random uncertainty in the measured voltage from the striker, which is then converted to a force. This is estimated by recording a time series of the noise floor and dividing by the sensitivity. Note that the striker is calibrated *in-situ* with the same voltage digitizer that is used to break samples, so that absolute SI-traceability of the voltage digitizer does not need to be established, as long as the two instruments are considered a mating pair. Other effects, such as long-term voltage drift, are neglected.

The dynamic uncertainty u_{dyn} accounts for differences in the static and dynamic sensitivity of the device. A detailed explanation may be found in Ref. [X1]. This uncertainty is represented by:

$$u_{\text{dyn}}^2 = \frac{p^2}{3} \ , \tag{X4}$$

where:

$$|p| \le \frac{1}{2\pi} \int_{-\pi}^{\pi} B(\omega) |SG(\omega) - 1| \, d\omega \ . \tag{X5}$$

Here, $B(\omega)$is a bounding function on the coefficient of the estimated input force profile in the frequency domain, S is the static sensitivity, and $G(\omega)$ is the complex frequency response function of an inverse system, which approximates the inverse of the frequency response function obtained from the dynamic calibration.

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