

SURVEY OF PUBLISHED EDDY CURRENT EXPERIMENTATION FOR APPLICABILITY TO HYBRID DIGITAL TWINS

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ABSTRACT

A survey of published eddy current experimentation was conducted to assess for applicability to hybrid digital twins that use neural network-based system transfer functions. More than 37 experiments in 33 publications were surveyed. No implications were given that any publication surveyed was found to be deficient in a general manner. Neither experimental reproducibility nor publication results reproducibility were evaluated in this survey. Certain variables are critical when publishing experimentation with the intention of that data being applicable to an eddy current hybrid digital twin. These variables are categorized into virtual reproducibility and data application. The applications of the data are presented in workflow diagrams. Commercial system results are used to train a system transfer function, and impedance analyzer results are used as supplemental data for enhanced decision-making. Survey results were used to develop and propose guidance in the form of an operational checklist for reporting eddy current experimentation results, improving applicability not only to hybrid digital twins but also to eddy current digital twins in general. The use of this checklist for published eddy current experimentation should help improve data availability within the industry. Increased data availability is an enabling factor for further development of digital twins in nondestructive evaluation.

KEYWORDS: eddy current, digital twin, VVUQ, NDT 4.0, nondestructive evaluation (NDE)

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Materials Evaluation 84 (7): 85–93
<https://doi.org/10.32548/2026.me-04583>
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Introduction

The development of digital twins [1–11] and model-assisted decision-making [12–18] remains an ongoing challenge for many researchers in nondestructive evaluation (NDE). Digital twins were first proposed by Michael Grieves [19] in 2002, but it was not until 2011 that the term “digital twin” was established by John Vickers [20] at NASA. In 2017, Grieves and Vickers published the first formal definition of “digital twin” [21], now known as the Vickers/Grieves digital twin. The Vickers/Grieves digital twin is a lifecycle management tool. Grieves [22] personally identified issues across industries in the definition of a digital twin, identifying 358 published definitions with varying applications and levels of novelty. In 2024, the National Academies of Sciences, Engineering, and Medicine (NASEM) published a formal definition of a digital twin across industries [23]. The NASEM digital twin expands the use of digital twins to all industries beyond their use as a lifecycle management tool. However, the NASEM digital twin can still be implemented as a lifecycle management tool, preserving the original purpose of the Vickers/Grieves digital twin. Moving forward, the term “digital twin” will refer to a NASEM digital twin [23]. The development of digital twins is possible with any NDE method that produces digital data, such as ultrasonic, X-ray, and eddy current testing (ECT). This survey focuses on eddy current; however, the absence of additional methods does not imply that the method is not applicable to digital twin technology.

Digital twins are categorized into types: data-centric, model-centric, or hybrid. Data-centric digital twins use machine learning or neural network algorithms, such as classification algorithms, to predict defect detection. A model-centric digital twin uses modeling and simulation, including simulation results on various defect dimensions to enable defect sizing prediction. ECT poses a challenge for model-centric digital twins: the model outputs complex impedance, while the commercial system reports signals in complex volts. This is normally addressed with transfer functions [24–27]. However, a digital twin in application could require the operator to have the capability to adjust system settings such as gain and drive voltage, which can cause significant issues with a mathematical system transfer function (STF). Neural network STFs [28, 29] have been shown to have that capability. An ECT digital twin that uses aspects of both data-centric and model-centric approaches is called a hybrid digital twin. Creating an ECT

hybrid digital twin requires both a modeled component and the initial physical data with identified settings to train and validate the STF. Once an STF has been validated, supplemental data can be integrated, such as impedance analyzer measurements.

The purpose of this survey is to assess the applicability of published ECT experimentation to the development of a hybrid digital twin. The survey has been broken down into two sections of STF training data and supplemental data based on the use of commercial ECT systems and impedance analyzers, respectively. The survey criteria for both sections remain relatively the same, with the only difference being in the application of the data, as illustrated in Figure 1.

The first criterion, as shown in Figure 1, is whether the experimentation can be modeled properly. To create a proper model of the experimentation, the entire experiment must be reproducible in the model. This means that the publication must identify the necessary variables for the probe and sample. The variables must be identified (not assumed) with corresponding units of measure and made available to readers, either within the publication itself, in supplemental

information, or through an accessible external source such as a prior publication or open-access archive. These variables include the sample's electrical conductivity, magnetic permeability, and defect characteristics such as dimensions, shape, and orientation. If the variable can be measured, such as the properties and dimensions of the inspection sample, it must be stated how they were measured. Otherwise, the values cannot be discerned from assumed or effective values and therefore treated as assumptions. Effective values of variables such as conductivity adjust model variables to match experimentation when those variables can be measured. For the purposes of this survey, the use of effective values rather than measured values is unacceptable for virtual reproducibility.

The virtual reproducibility of probes, both custom and commercial, can be challenging. All commercial probes in use must be identified so that peer researchers can obtain the same make and model for model development. However, even with commercial probes, it cannot be expected that two probes of the same make and model will have identical variables. The allowable assumptions in this survey are the relative magnetic permeability of known paramagnetic and slightly diamagnetic metals, such as aluminum, and variables associated with commercial standards and coil variables of commercial probes. For custom probes, the variables must be provided so that peer researchers can model an equivalent probe in terms of process, dimensions, material properties, and components.

Virtual reproducibility of inspection techniques and fixturing need not be difficult. The use of manual or hand scanning results is inherently unreliable enough for model development and therefore will be considered as not reproducible in this survey. Required variables for modeling are lift-off (Z axis), probe orientation (XZ plane and YZ plane), and the use of protective tape. The Z-axis rotation of the probe (in the XY plane) is an important variable for directionally sensitive probes, such as the common split-D type probe. Additional variables such as scan rate, acquisition rate, and scan path become necessary when performing dynamic inspections.

A second criterion, as shown in Figure 1, would be the inspection data and its capability to be used in either the training and validation of the STF for commercial experimentation or supplemental data for impedance analyzers. For commercial systems as shown in Figure 1a, the system settings that would influence the measured value must be reported. These variables include frequency, gain, rotation, and drive voltage. In the case of impedance analyzers as shown in Figure 1b, only the frequency is required. In either situation, if the results are presented in Lissajous form, the scaling or division units must also be provided. If the measured values are given, the unit must be reported along with the measurement method, such as null-to-peak or peak-to-peak, when reporting results from an automated scan. Normalized impedance planes are acceptable only if the normalizing value is clearly stated, such that the value does not have to be assumed or calculated by a peer researcher reading the publication.

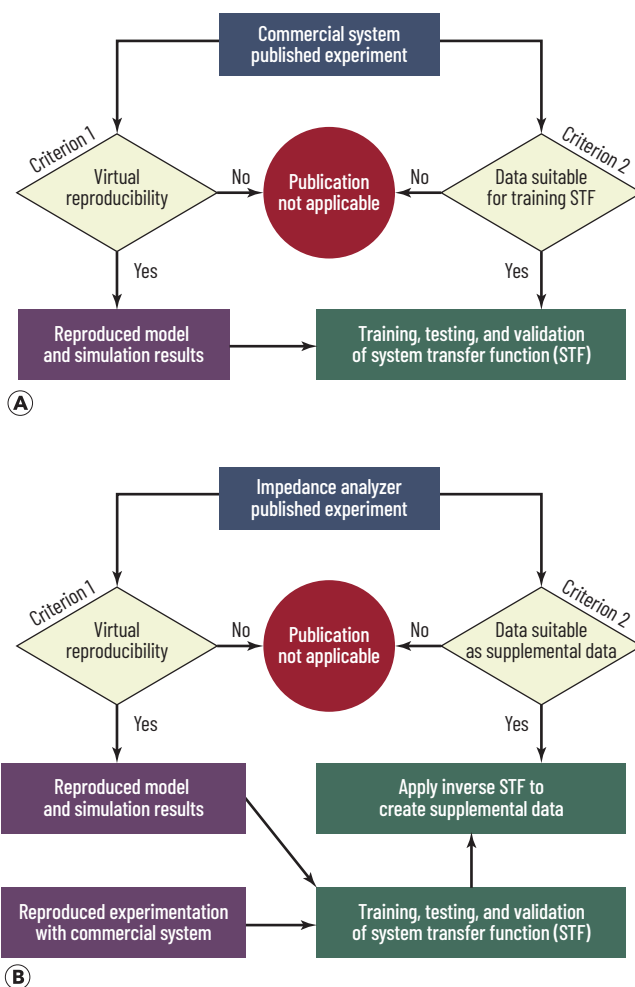


Figure 1. The published experimentation criteria workflow chart for: (a) commercial system; (b) impedance analyzer.

2. Survey

Thirty-three publications [39–62] containing ECT experimentation between 1988 and 2020 were surveyed. The publication selection process for the survey focused on conventional single-probe ECT inspections. For the purposes of this survey, ECT array inspections are not considered conventional single-probe ECT inspections. This is due to ECT array probes consisting of multiple coils and/or Hall effect sensors that enable the array to operate in absolute or reflection modes. This allows for different output channels with directionality components. In added complexity, modern ECT array probes have flexible electronics that enable area inspections on curves with reduced liftoff concerns. The results of ECT array inspections can be presented as Lissajous, A-scans/strip charts, or C-scans. The additional complexity of developing a validated model of ECT array inspections, as compared to single-probe inspections, would require more variables and greater scrutiny for published ECT array experimentations. The approach demonstrated by this survey should be applied to ECT array inspections, especially when considering the relevance of ECT array in modern NDE and the integration of digital engineering. However, for the purpose of demonstrating this approach and presenting it as a foundation for evaluating the necessary information to develop an ECT hybrid digital twin, published ECT array experimentations are not included in this survey.

The tabulated results for each reviewed publication include the reference number, description, and columns indicating whether the experimentation can be virtually reproducible and can be used based on the applicable section. The commercial system section determines whether the published data can be used to train and validate STFs, while the impedance analyzer section determines whether the published data can be used as supplemental data. Some of the publications contain more than one experiment. If the assessment of the individual experiments yielded different

conclusions, the tabulated information will be separated. Otherwise, all the experimentation will be consolidated into a single row. Tables 1 and 2 are for quick reference and show the binary conclusion for the corresponding established criteria. The reasons for the classifications are discussed in the text corresponding to the tables. Of the 33 publications surveyed, nine of them [30–38] could not be identified as commercial systems or impedance analyzers. Therefore, those publications cannot be classified into either section of the survey and cannot be used in either capacity.

2.1. Commercial System Experimentation

The survey of commercial system experimentation is shown in Table 1. Kane and Koshti [39] is a published report complete with procedure, results, and system settings. This report identifies commercial equipment in a traceable manner and system settings sufficient for virtual reproducibility in accordance with commercial standards. The results of the experimentation are tabulated in a serialized appendix. Assumptions must be made for the shape of the cracks measured. The crack specimens are not virtually reproducible without any shape information. However, the commercial standards are virtually reproducible within the acceptable assumptions stated previously.

Lahdenperä [40] lacks sufficient system settings or results data for STF training and is not virtually reproducible due to assumptions required for conductivity and permeability. This is especially important with austenitic stainless steel undergoing welding and inducing thermal cracks. Ibrahim et al. [41] are missing the necessary information on the probes used in the experimentation that is required for virtual reproducibility. No drive voltage setting is given. Gain is discussed and used as a normalization technique between cracks and notches, but no gain settings are available. Rotation is adjusted to place the indication in the vertical position for each measurement, but the rotation values are not provided.

TABLE 1
Survey of published commercial systems experimentation

Reference	Description	Virtual reproducibility	Data suitable for training STF
[39]	Kane and Koshti commercial standards	√	√
[39]	Kane and Koshti crack specimens		√
[40]	Lahdenperä		
[41]	Ibrahim et al.		
[42]	Kyrgiazoglou and Theodoulidis		
[43]	Feistkorn et al.		
[44]	Oswald-Tranta et al.		
[45]	Camerini et al.	√	
[46]	Lo et al.		
[47]	Mohseni et al.		

Lastly, the results are presented as percentages of amplitude at various gain values. Overall, the presented data cannot be used for training STFs.

Kyrgiazoglou and Theodoulidis [42] do not identify the material of the samples or the necessary information on the commercial probe used in the experimentation. The material properties reported were the effective simulation parameters used to match the experimental results. Therefore, the published experimentation is not virtually reproducible. The units reported for the results were stated to be arbitrary. System settings required for training STFs were not reported. Feistkorn et al. [43] and Oswald-Tranta et al. [44] appear to report on the same experimentation and results. Both reports provide the part numbers for the probes to be traceable; however, the information provided about the probes in the publications contradicts the information provided by the manufacturer. Overall, both publications [43, 44] are neither virtually reproducible nor able to train STFs.

Camerini et al. [45] report very well for the virtual reproducibility of the experimentation for the notch samples due to the notch being through-thickness and much longer than the probe dimensions given. However, the reported data cannot be used to train STFs due to missing phase results and settings information. Lo et al. [46] do not report the necessary probe information for virtual reproducibility. The resulting data and system settings cannot be used to train STFs. Mohseni et al.

[47] identify the variables required for virtual reproducibility; however, the values are not reported. The required settings and results for training STFs are not reported.

2.2. Impedance Analyzer Experimentation

Overviews of the surveyed impedance analyzer experimentation are shown in Table 2. The natural starting point for this section of the review is with benchmark studies. Given the nature of benchmarks, virtual reproducibility is expected. Benchmark Test 1 [48] provides a baseline for the impedance analyzer section of the survey. Sufficient information was given to reproduce the manufacture of the custom probe and specimen. Error measurements were even given with dimensional measurements, conductivity, and inductance. Techniques for measuring the defect dimensions and specimen conductivity were also described. Sufficient information on the impedance analyzer, leads, frequency, technique, and resulting isolated coil measurements was given for virtual reproducibility. Information was also given for the calibration of the system, and additional measurements were recorded for liftoff to provide further verification and control of variables that improve virtual reproducibility. All units of measure were identified, and the results were not scaled or normalized. Results were, however, published in inductance and resistance rather than complex impedance. The inductance and resistance values can still be used for

TABLE 2
Survey of published impedance analyzer experimentation

Reference	Description	Virtual reproducibility	Suitable as supplemental data
[48]	Burke; Benchmark Test 1	✓	✓
[49]	Benchmark Test 2: Rectangular slot in a thick plate	✓	✓
[49]	Benchmark Test 3: Crack in a thin plate	✓	✓
[49]	Benchmark Test 4: Cracks in a double plate system	✓	✓
[49]	Benchmark Test 5: Cracks in a thin plate (tangent coil)	✓	✓
[52]	Benchmark problem D1	✓	
[52]	Benchmark problems D2-D4		
[53]	Chady and Sikora benchmark problem		
[54]	Martinos et al. 2013 benchmark	✓	✓
[55]	Martinos et al. 2014 benchmark	✓	
[56]	Barbato et al. benchmark	✓	
[57]	Ditchburn et al.	✓	
[58]	Burke et al.	✓	
[59]	Theodoulidis et al.	✓	
[60]	Bowler et al. March 2012	✓	✓
[61]	Bowler et al. December 2012	✓	✓
[62]	Miorelli et al.	✓	

model validation, which would allow for this data to be used supplementally.

Benchmark Test 2 [49] reports the variables for virtual reproducibility and use as supplemental data in the same manner as Benchmark Test 1 [48]. The specimen, system, and technique are identified to be the same. Benchmark Test 3 [49] presents the results in the same manner as previous benchmarks and cites a study by Burke and Rose [50] that contains the necessary information for virtual reproducibility. Benchmark Test 4 [49] increased the complexity of the previous benchmark by citing Burke [51], in which the coil construction is the same coil as the one used in Benchmark Test 3's citation of Burke and Rose [50]. Even with layers of citations, Benchmark Test 4 [49] meets the baseline of virtual reproducibility and can be used as supplemental data. Benchmark Test 5 [49] contains no cited experimental section. The coil is the same type used in prior benchmarks. Virtual reproducibility use as supplemental data is shown for Benchmark Test 5 [49].

Benchmark problems D1–D4 [52] are published together. However, only D1 has a reported measured conductivity, whereas the remaining benchmarks only have effective conductivity. This results in D1 being the only virtually reproducible experimentation of the four. All four of the benchmarks report the normalized data without reporting the normalizing value, and therefore none of the benchmarks D1–D4 [52] meet the requirement to be used as supplemental data.

The Chady and Sikora [53] benchmark problem uses a complex probe with a single ferrite core for five coils. The reported probe variables are assumed and not measured. Supporting information and results data are not provided in a citation or archive. An email is provided for requesting information; however, it is not reproducible virtually or usable as supplemental data per the survey criteria. The Martinos et al. [54] benchmark of single and multilayered structures reports three test cases with all necessary information for virtual reproducibility and use as supplemental data. The Martinos et al. [55] benchmark was published a year later and reports four additional configurations of both single- and double-layer inspections, with all necessary information for virtual reproducibility. However, the normalizing value of the reported data is not reported, so the benchmark cannot be used as supplemental data. The Barbato et al. [56] benchmark cites and uses the same four experimental configurations as Martinos et al. [55]. The same issue with the reporting of the data results in the benchmark being unable to be used as supplemental data.

Both Ditchburn et al. [57] and Burke et al. [58] meet the baseline for virtual reproducibility with ferromagnetic specimens. The verification and control of variables with ferromagnetic specimens are noteworthy because they enable magnetic permeability measurements. However, neither publication provides the normalizing value of the reported normalized results. It is not stated whether that reactance value was calculated from the measured or calculated inductance. Theodoulidis et al. [59] identified the variables for virtual

reproducibility but did not specify a normalizing value for the results. Bowler et al. in March 2012 [60] and Bowler et al. in December 2012 [61] provide all the necessary information for virtual reproducibility. The work of Bowler et al. in March 2012 [60] serves as an example of specifying notch shape. The results of both were not normalized and therefore can be used as supplemental data. The work of Miorelli et al. [62] identifies sufficient variables for virtual reproducibility and serves as an example for identifying notch orientations. Inductance was both measured and calculated. The calculated inductance was stated to be used as the normalizing reactance value, but it was not provided. Therefore, the publication does not meet the requirements of supplemental data.

3. Discussion

Thirty-seven individual experiments were surveyed, and more when considering instances with multiple experiments of the publication are summarized in a single row in Tables 1 and 2. The benchmark studies and other impedance analyzer publications showed a clear trend toward virtual reproducibility, whereas the commercial publications showed the opposite. The commercial system experimentation survey results overall show difficulty in meeting the criteria. This is most likely due to industry norms that do not include all system settings and other variables when reporting experimental results from commercial systems. The results of the impedance analyzer experimentation survey showed a clear advantage in virtual reproducibility, driven by the benchmarks and the computational focus of the remaining papers. The apparent trend among the publications identified as unusable as supplemental data was the normalization of the reported results. This is also an industry norm. Ideally, in that instance, the computational results should be normalized by the computed reactance, and the experimental results should be normalized by the measured reactance. However, when that was not clearly stated with the values provided, assumptions must be made about the values. Developing a digital twin with such assumptions occurring with supplemental data or STF training data is unacceptable. This is because a key aspect of digital twins is the verification, validation, and uncertainty quantification of every component and process.

3.1. Proposed Operational Checklist

A proposed operational checklist has been developed for eddy current experimentation applicability to a hybrid digital twin using a neural network STF [28, 29], as shown in Table 3. The incorporation of the proposed operational checklist into future published eddy current experimentation is expected to enhance data availability and support continued digital twin development in eddy current NDE. The proposed operational checklist can also be easily modified for use in other methods, such as ultrasonic NDE.

TABLE 3

Proposed operational checklist for future published eddy current experimentation applicability to a hybrid digital twin using a neural network-based system transfer function

SYSTEM		
Component	Section	Example
Commercial system	Manufacturer	Zetec
	Part number	21C
	Frequency	125 kHz
	Rotation	36°
	Drive voltage	10 V
	Gain	1:1 @ 30 dB
	Results	Complex volts (V)
	Measurement type	Null-to-peak
	Null location	Defect-free sample
Impedance analyzer	Frequency	125 kHz
	Results	Normalized complex impedance (Ω)
	Normalizing value (if applicable)	$X_o = 123 \Omega$
PROBE		
Commercial probe	Manufacturer	Zetec
	Part number	DPT45U
Custom probe	Coil 1 shape	Circular
	Coil 1 height	10.12 mm
	Coil 1 inside diameter	3.07 mm
	Coil 1 outside diameter	4.23 mm
	Coil 1 core	Air
	Coil 1 core dimensions (if applicable)	n/a
	Coil 1 core measured/calculated conductivity (if applicable)	n/a
	Coil 1 core measured/calculated magnetic permeability (if applicable)	n/a
	Coil 1 shielding	n/a
	Coil 1 shielding dimensions (if applicable)	n/a
	Coil 1 stand-off	1.34 mm
	Coil 1 wire size	28 AWG
	Coil 1 turns	225
	Coil 1 activity	Absolute (transmit and receive)
	Information as above for additional coils (if applicable)	n/a
	Configuration and spacing of multiple coils (if applicable)	n/a

(cont'd next page)

TABLE 3 (CONT'D)

Proposed operational checklist for future published eddy current experimentation applicability to a hybrid digital twin using a neural network-based system transfer function

FIXTURING		
	Scan path	Perpendicular to defect
	Starting location	8 mm from defect center
	Step size	0.2 mm
	Scan speed	1 mm/s
	Acquisition rate	25 Hz
	Liftoff	0.35 mm
	Tilt	Perpendicular to surface
SAMPLE		
Commercial standards	Manufacturer	UniWest
	Part number	78222
Non-commercial standards	Material	7075-T651 Aluminum
	Measured/calculated conductivity	36% IACS
	Measured/calculated relative magnetic permeability	1
	Sample shape	Plate
	Sample measured length	100 mm
	Sample measured width	50 mm
	Sample measured thickness	12 mm
	Defect type	EDM notch
	Defect shape	Rectangular
	Defect measured length	10 mm
	Defect measured width	0.01 mm
	Defect measured depth	1 mm
	Defect orientation	Parallel to sample width
	Defect location	Centered on sample

4. Conclusion

This survey has not called into question the reproducibility or quality of the published works that were surveyed. It has, however, identified the need for stricter guidance for published experimental data to be used in the development of an eddy current hybrid digital twin that uses a neural network STF. The workflow of these applications has been identified and guidance has been provided in the form of an operational checklist. The use of this checklist for published eddy current experimentation should improve data availability and enable further development of digital twins in NDE.

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