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The Use of Modal Testing within Nuclear Weapon Dismantlement Verification

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The technical verification of a possible future nuclear arms control agreement is a complex challenge for technology developers. The focus of this article is on the use of modal testing techniques as a method for maintaining a chain of custody over containerized treaty accountable items (TAI) and monitoring equipment. Modal testing is a specialized form of resonant vibration analysis often used for the purpose of structural identification, condition monitoring, and damage detection. From a chain of custody perspective, it was postulated that a modal vibration signature might be used to identify a particular treaty accountable container or container/object system, or provide evidence of tampering. This article considers the advantages and disadvantages of modal testing as a potential chain of custody tool. Experimental results are discussed relating to deployment, tamper indication, unique identification and data analysis methodology.

THE TECHNICAL VERIFICATION CHALLENGE

The Arms Control Verification Research (ACVR) program undertaken at Atomic Weapons Establishment (AWE) investigates and develops methodologies and technologies which could be deployed to verify possible future nuclear disarmament agreements.[1,2,3,4] The program considers hypothetical bi-lateral or multi-lateral scenarios involving the dismantlement of nuclear warheads. The focus at this time is on a generic scenario which follows the nuclear warhead from arrival at an initial storage facility, through various transport and dismantlement phases, to the storage of fissile components. In

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this scenario, the process would be overseen by a “monitoring party” with reference to processes and facilities controlled by a “host party.” Monitoring, in this context, is the technical process of gathering information to ascertain whether the relevant parties are in compliance with the provisions of an international agreement. The hypothetical declarations considered during this work contain a reference to a treaty accountable item (TAI) (e.g., a complete warhead, a partially dismantled warhead, a fissile component, or fissile material).

One of the key drivers influencing the development of the final negotiated technical monitoring regime, and the selection of technologies, is the differing perspectives of the parties involved. The host party, whilst wishing to facilitate the monitoring process, has an obligation to protect sensitive or proliferative information relating to the TAI, the facility, or operations undertaken within the facility. Despite any restrictions this situation may impose, the monitoring party will wish to gain confidence that the TAIs are as declared, have not been tampered with, and that no treaty relevant items/materials have been diverted from the process. This leads to the main challenge for any verification regime operating within a nuclear weapon complex: to provide the monitoring party with the opportunity to gather sufficient evidence of compliance, whilst protecting sensitive or proliferative information held by the host. The final monitoring regime must balance these two viewpoints and take account of any resulting constraints that may be imposed.

Although this article discusses one particular aspect of a monitoring regime, chain of custody, this should be viewed as one element of the overarching regime design. Device and material monitoring, chain of custody, authentication, certification, data management, and managed access need to be brought together, and balanced, to create a mutually acceptable level of confidence in the overall verification system.[5]

CHAIN OF CUSTODY

Chain of custody is an integrated series of procedures and technologies designed to account for treaty relevant items throughout a treaty accountable process, and provide confidence that the integrity and authenticity of an item has been maintained.[6,7] From the perspective of the monitoring party, chain of custody provides:

- Monitoring of access to TAIs.
- Control over monitoring equipment and data.
- Confidence that no attempt has been made to tamper with, spoof or divert TAIs, monitoring equipment or data.

- The link between the various technical measures required to establish the identity and authenticity of the TAI.

Boundary control and signature tracking (sometimes referred to as one-to-one templating) are two strategic methodologies used in the development of chain of custody systems. Boundary control methods look to create a designated, controlled, perimeter around a TAI, monitoring equipment or work area. The most obvious manifestation of a boundary control concept is the tamper indicating enclosure (TIE). Traditionally these are viewed as "boxes" which provide evidence of an unauthorized attempt to gain access to a sensitive asset. However, the actual realization of the boundary control approach could take many forms, and might be implemented on many different levels of scale from individual assets through to facility level areas.[8–13] The key to creating a robust boundary control system is the integration of multiple tamper indicating and uniquely identifying (anti-counterfeiting) technologies into one, multilayered, optimized design.

Signature tracking, the focus of this article, is a complementary approach to creating a controlled boundary. A signature relating to a given containerized object is recorded before the object moves out of the direct control of the monitoring party (for example into storage or into a transport phase). At a future point in time the object is re-inspected, the measurement is taken again, and a comparison made. The objective in this approach is to ascertain whether the signature has changed, thereby indicating that some level of unauthorized interaction has taken place. By considering signature tracking from this perspective a number of points emerge:

- Unlike boundary control technologies which are placed around an asset, signature tracking concepts utilize a measurement that is either directly linked to the asset itself, or to a given container/asset combination. Note that the monitoring party is unlikely to be given full access to the TAI, but instead be presented with a series of containerized objects, each representing a different point in the dismantlement process.
- This approach could have advantages in situations where boundary control might be difficult to realize (e.g., during transport phases).
- Signature tracking could be challenging to implement during periods where the object might change configuration (e.g., during the dismantlement process itself).
- The approach could be implemented more widely than just the TAI; chain of custody relating to monitoring equipment could also be considered.

- From a chain of custody standpoint, ionizing radiation is not the only option that could be used as the underpinning signature for such an approach.[14] However, the chosen signature would need to:
    - Uniquely identify the container/object system.
    - Provide evidence of tampering with the container, or evidence of tampering with the contents of the container.
    - Remain stable over the timeframe between inspection periods and constant (or predictable) with respect to background environmental factors.

Both parties would need to consider whether there is potential for the release of proliferative information; the host party would also have to consider the protection of nationally sensitive information. As signature tracking techniques record a measurement directly associated with a potentially sensitive asset, an information barrier might be required in support of this approach.[15]

Given the potential complexity of overarching chain of custody regimes, multiple technologies are required to provide the flexibility to respond to different scenarios, to provide multiple levels of evidence, and to avoid the vulnerability of a single point of failure. As science advances, and potentially creates more sophisticated modes of attack, existing technologies must be reviewed and additional technologies considered. With this in mind, the chain of custody program at AWE explores a variety of signature tracking techniques for use in the context of treaty verification. Modal testing was proposed as one potential approach.

AIMS OF THE EXPERIMENTAL CAMPAIGN

A series of experiments were devised to investigate the use of modal testing as a signature tracking chain of custody technique. This article presents and discusses the results from that experimental campaign, which had the following aims:

Deployment: Assess this technique for speed, portability and ease of use.

Data Analysis Approach: Determine the optimum approach for analyzing the data acquired.

Repeatability: Investigate the repeatability of the measured output, and devise an analytical method for classifying the results to support a judgment by the operator on whether a significant alteration has occurred within the container/object assembly.

Unique Identification: Assess the ability of this technique to uniquely identify a given container or component part of that container.

Tamper Indication: Assess the ability of this technique to provide evidence of an unauthorized attempt to either: move the container, enter the container via the normal point of entry or breach the side of the container and repair the area.

Internal Configuration: Assess whether this technique has the potential to highlight a change in the internal configuration of an object inside a test container.

During the planning phase, an overarching modal testing methodology was devised which encompassed the general approach to be taken during both the experimental and data analysis phases. Simulant test containers were developed to support the campaign; the experimental set-up was optimized for speed of deployment before the final experimental campaign was undertaken.

THE MODAL TESTING METHODOLOGY

All solid objects can be excited into mechanical resonance. An obvious example of this is the audible output when a bell is struck. The structure of the bell has inherent resonant frequencies; at a given resonant frequency the structure will assume a "standing wave" form known as a modeshape. The dominant modeshape results in the tone that we hear and will change if the bell is significantly altered or damaged. Modal testing is a specialized form of resonant vibration analysis which uses this property for the purpose of structural identification, condition monitoring and damage detection.[16] From a chain of custody perspective, it was postulated that this structural testing method might also be used to uniquely identify a container with a given object inside, and highlight changes resulting from tampering.

Future nuclear disarmament verification activities are likely to take place within a restrictive managed access regime.[17] Therefore it was felt that the measurement system needed to be assembled quickly, portable, and easy to use. A typical modal testing experiment involves an excitation method which imparts a force into the structure, and a response measurement looking at the acceleration, velocity or displacement of the surface. After consideration, a modal hammer was selected to provide and measure the force into the structure, and a tri-axial accelerometer was selected to record the vibration response in the X, Y, and Z directions (Figure 1). This choice does not rule out other approaches, but it was felt that this is the simplest approach to deploy and therefore a reasonable set-up for this preliminary experimental campaign.

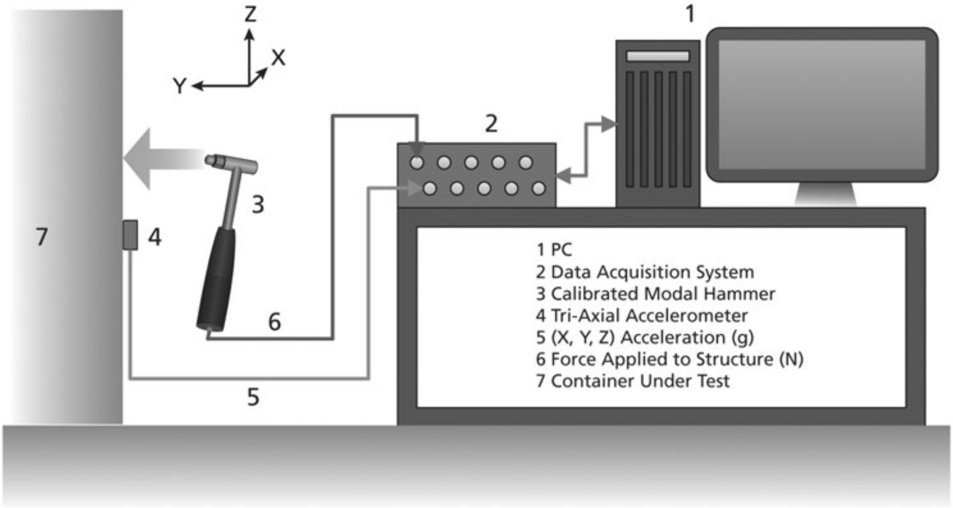

Figure 1: A calibrated modal hammer was used to provide and measure the force applied to the structure, and a tri-axial accelerometer was used to record the vibration response in the X, Y, and Z directions (1 g = 9.81 ms^{-2}).

Typically, tri-axial accelerometers would be placed at multiple points on a structure; the modal hammer is used to strike the structure at a specified point. The system then records (Figure 1):

- The force imparted by the hammer into the structure.
- The X, Y and Z response from the accelerometers.

In terms of terminology, the ‘drive point’ is the response from the accelerometer nearest the point of impact, in the direction of that impact; the responses from the accelerometers at other points on the structure are referred to as “transfer points.” Although these measurements are made in the time domain, it is necessary to convert the signals into frequency domain based spectra for further processing. At this point, the frequency response from the accelerometers is divided by the measured input force imparted by the hammer to obtain the frequency response function (FRF) (Figure 2). If the structure and experimental set-up has a linear response within the range of forces used during a given experimental campaign, this normalized FRF response will be independent of the imparted force. It is therefore important to confirm linearity with input force during experimental set-up. For each hammer impact location, this experimental set-up provides three FRF curves from each tri-axial accelerometer (X, Y and Z).

Stimulating an un-damped system at one of its resonant frequencies would result in an infinite response. In practice, damping (energy loss mechanisms)

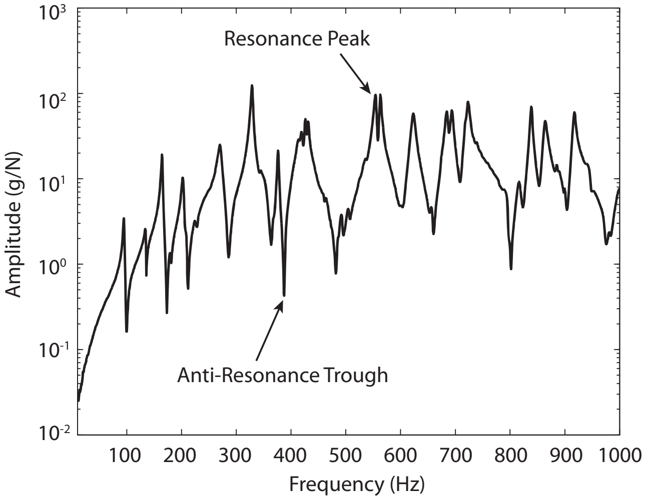

Figure 2: A graph showing a typical acceleration frequency response function spectrum. In the frequency domain, this represents the vibration response normalized by the input force (1 g = 9.81 ms^{-2}).

limits the response amplitude to some finite value, which is marked by peaks in a given FRF spectrum (Figure 2). The position and amplitude of these peaks derive from the mass, stiffness and damping of a structure under test, and will therefore be affected by a significant structural change. Joints/interfaces might also influence the overall response of the container, as it was noted from previous experience that the re-assembly of a structure containing joints rarely yields the same overall FRF response. Again, this adds to the unique properties of a given assembly and might also be indicative of an unauthorized attempt to enter and then re-assemble the structure.

There are many approaches to analyzing FRF curves;[18] two common approaches were selected to support this experimental campaign:

- One-to-one analysis
- Global criterion (GC) analysis

For one-to-one analysis, two FRF curves are selected and overlaid; a simple, qualitative, graphical comparison is then made by a subject matter expert. It is not practical to consider all FRFs during a one-to-one analysis, so spectra are selected which provide the most information. Typically a subject matter expert would begin with the drive point FRFs before considering transfer points. Note that traditional modal testing analysis would only consider the position of the peaks within a given FRF spectrum. For this scenario it was felt that additional information might be present in other spectral regions and therefore the whole spectrum should be considered.

One-to-one analysis can be extremely useful but it typically requires a highly skilled practitioner to compare data collected from structure A with like-for-like data from structure B. This analysis is always completed by comparing just two FRFs at a time, which can be a painstaking process. Also the results of such an analysis are always qualitative since they rely on subjective (albeit expert) judgment. It would be desirable in this scenario to have an impartial, automated comparison tool which would be able to deal with all the data generated by the tests. An analysis package was developed for this purpose which was based on the GC. Mathematically, GC provides a metric for comparing the amplitude and shape of FRF data sets. Across the specified frequency range, GC calculates the amplitude and shape correlation functions (χ_a and χ_s). This provides a value between one and zero; one indicating 100 percent correlation and zero indicating 0 percent correlation.

EXPERIMENTAL SET-UP

In this hypothetical scenario, the monitoring party would deploy a modal testing based technique to the outside of a container which may, or may not, contain a TAI. In order to simulate this, these experiments used nine nominally identical metal test containers, each approximately 1 m^3 in volume (Figure 3). Each container comprised:

- A base unit which consisted of a cylinder attached to a heavy base.

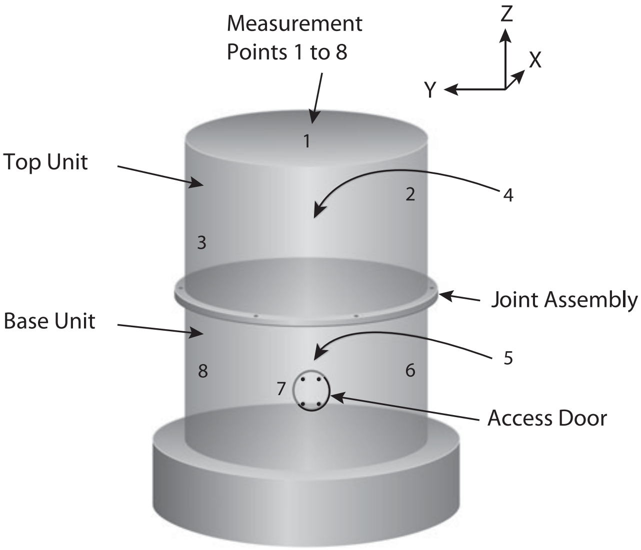

Figure 3: Illustration showing the test container set-up and the eight measurement locations.

- A top unit consisting of a cylindrical cover.
- A bolted joint assembly which connected the cylindrical base unit to the cylindrical top unit to create the closed container.
- An access door in the base unit.
- A serial number designated TC-(A to I).

The base unit was significantly stiffer and heavier than the top unit. This meant that the effect of a non-uniform container structure could be explored as a part of the experimental scenario. To simulate the presence of an object inside the container, a test mass and supporting internal furniture were also created.

Substantial effort was devoted to finding the optimal test set-up in terms of the method of excitation/response measurement, the design of the test coordinate system and location of the excitation/response points. The aim of this phase, which took approximately four hours to complete, was to ensure that the experimental design:

- Was fast and easy to deploy.
- Sufficient to provide coverage across all component parts of the test container.
- Would minimize the measurement of sensitive or proliferative parameters.

A typical modal testing experiment would use analytical models to optimize an experimental design. The Host may consider detailed design information about the certain container/object systems to be sensitive and withhold the information required to generate such a model. It was therefore concluded that in this scenario an experimental optimization approach might be more appropriate.

A subject matter expert selected a number of excitation and response locations on a given test container; an iterative series of experiments allowed the operator to optimize the experimental set-up. A frequency range (0 to 1 kHz) was selected that would contain a suitable number of resonances to support one-to-one and GC analysis (of the order of 20). Measurement locations were selected which would excite/detect all resonances in the given frequency range.

To aid in the detection of a tamper event, measurement locations were selected on every major section of the test container. The number of measurement points was kept to a minimum in order to decrease deployment time and restrict the measurement of “sensitive” information. A consistent coordinate system was used throughout the measurement campaign (Figure 3). It was found that eight measurement locations were sufficient to give full coverage of the test container. Accelerometers were placed at two locations on the top unit (1 and 3) and four locations on the base unit (5, 6, 7 and 8); the hammer provided excitation at four locations on the top unit (1, 2, 3 and 4) and four locations on the base unit (5, 6, 7 and 8). This measurement routine resulted in 72 FRFs being obtained per test container. The data acquisition system was a commercially available National Instruments PXi system with M+P SmartOffice acquisition software. The hardware and software were not altered from their standard configuration.

An experimental campaign was implemented targeting the goals of this project associated with deployment, repeatability, unique identification, tamper indication, and internal configuration. An initial survey of results, via one-to-one analysis, showed that drive point FRFs showed the greatest change for a given tamper; changes in the transfer functions were more subtle and less suited to the one-to-one analysis approach. As the transfer functions might also hold important information, the GC analysis tool was designed to compare all 72 FRFs from one dataset with all 72 FRFs from a second dataset. The drive point FRFs from all the measurements were analyzed via the one-to-one technique; a subset of the datasets were then selected and compared via the GC analysis tool. For the repeatability, unique identification and tamper indication measurements, the test containers were setup with full internal furniture and no test mass.

RESULTS AND DISCUSSION

Deployment

The measurement process was assessed in terms of speed of deployment, ease of use, and portability:

- It took approximately ten minutes for one operator to characterize one container/object configuration. A shorter test might be possible by using a data acquisition system with a greater channel capacity.
- The testing could be carried out relatively easily by an operator with only a few hours of training, but significant experience was required to troubleshoot technical difficulties.
- The chosen modal testing set-up (hammer and accelerometers) was easily portable, with both mains and battery powered versions available.

Given the above, the technique was found to be fast, robust, portable, and easy to deploy by multiple monitoring teams. This assumes that the system would be deployed as planned and that no issues arose, as resolving an anomaly could require significant experience on the part of the operator.

Repeatability

Repeatability was tested under five different conditions:

1. Nominally identical retest.
2. Linearity with force excitation.
3. Different test engineers, nominally identical measurement routine.
4. Different test engineers undertaking the set-up procedure (i.e., the marking of measurement locations) and measurement routine.
5. The location of the excitation and response points.

One-to-one analysis of the FRF spectra demonstrated that the results were repeatable and linear, and were therefore independent of the force imparted to the container (within the range of forces used during this experimental campaign). The analysis also showed that the results were independent of operator, both in terms of measurement routine and measurement set-up. This is an important observation as it is likely that several different monitoring teams would be deployed during the course of a monitoring regime. The set-up was also tested in terms of sensitivity to the location of excitation and response points. It was found that as long as the excitation and response points were placed within ±5 mm of the ideal location, the measurements were repeatable. This was found to be easily achievable in practice.

While considering the practicality of deploying this system, it was decided that a measurement classification system might be required. This system would be used by the operator as the basis for a decision making process, supporting either the acceptance that no alteration had occurred or the initiation of an anomaly resolution procedure. In order to demonstrate a simple example of how this might be implemented, GC analysis was performed on the data sets from two of the experiments:

- Nominally identical re-test ($\chi_s = 0.95$; $\chi_a = 0.96$).
- Different test engineers undertaking the set-up procedure (i.e., the marking of measurement locations) and measurement routine ($\chi_s = 0.94$; $\chi_a = 0.95$).

These measurements of experimental repeatability provided a baseline for the GC results from which a classification system could be devised. For example, the nominally identical re-test indicated that results of $\chi_s = 0.95$ and $\chi_a = 0.96$, or higher, would indicate "no tamper" or an "undetectable change." However, a scenario involving a different test engineer undertaking the measurement procedure resulted in a lower correlation, indicating a region of potential ambiguity where results may be indicative of either tamper or experimental variability. This analysis of the GC results was used to

Table 1: Classification of GC analysis results.

	Mean Average Correlation Values		
Category	Shape (χ_s)	Amplitude (χ_a)	Classification of Result
1	$\chi_s > 0.95$	$\chi_a > 0.96$	Baseline or undetectable change
2	$0.95 > \chi_s > 0.93$	$0.96 > \chi_a > 0.94$	Minor change Without additional analysis this could be attributed to operator or experimental based factors.
3	$\chi_s < 0.93$	$\chi_a < 0.94$	Major change outside anticipated operating parameters.

set approximate boundaries to classify GC observations (Table 1). Three categories were discussed: (1) a baseline or undetectable change; (2) a minor change that would require further analysis to confirm that it was not due to operator or experimental parameters and; (3) a major change outside anticipated operating parameters. Minor and major changes would prompt the monitoring party to investigate other areas of the chain of custody regime for corroborating evidence as well as examining the results via one-to-one analysis. This classification system was used when discussing the results from the rest of the campaign. Clearly this is a simplistic and qualitative approach to determining classification boundaries; further work would be required to create a robust and unbiased classification system suitable for deployment.

Unique Identification

The FRF spectra from six nominally identical test containers were compared to see if there were sufficient differences in the FRF spectra for this technique to be used for unique identification. One-to-one analysis showed that the curves were container specific (Figure 4); this was supported by the GC analysis which demonstrated a major change in the associated correlation values when FRFs from different containers were compared ($\chi_s = 0.78$; $\chi_a = 0.79$). The curves for each test container had a similar number of resonances between 200 Hz to 1 kHz, but differed in terms of the frequency and amplitude of the peaks (Figure 4). Note that the peaks in the FRF spectra from the base units lacked the clear definition seen from the top units (Figure 5). This is due to the energy loss mechanisms (damping) caused by the joint assembly and the coupling of the base unit to the floor.

A second experiment was conducted where the top units from two containers were swapped. One-to-one analysis showed subtle changes in peak frequency and amplitude that indicated that a configuration change might have occurred. The GC analysis showed decreased correlation values indicating a

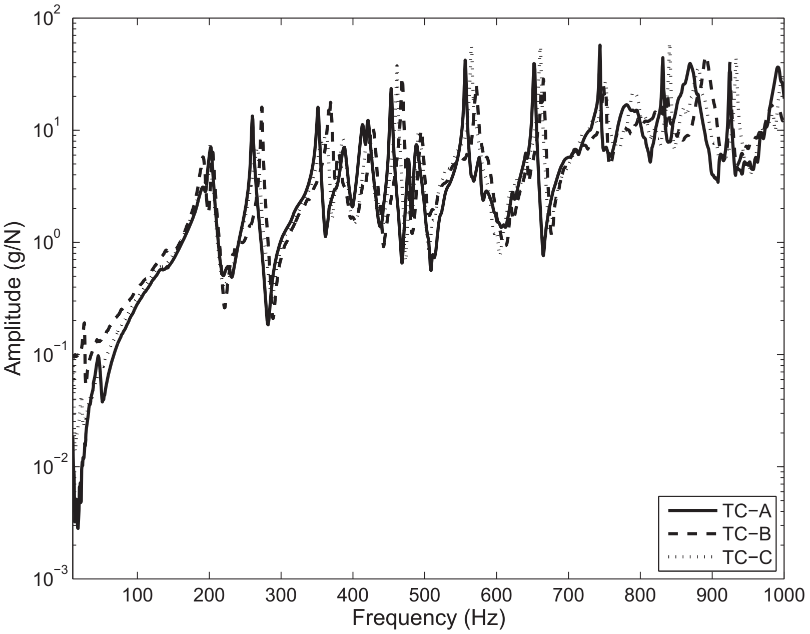

Figure 4: Example frequency response function spectra from three nominally identical test containers (response and excitation at position 3, axis Y). The curves for each test container have a similar number of resonances between 200 Hz to 1 kHz, but differ in terms of the frequency and amplitude of peaks (1 g = 9.81 ms^{-2}).

major change for the base unit ($\chi_s = 0.91$; $\chi_a = 0.92$) and a minor change for the top unit ($\chi_s = 0.94$; $\chi_a = 0.95$). This was further confirmation that the identifying signature relates to a specific container configuration.

Tamper Experiments—Moving the Container

The container was moved between four locations and measured at each point ((1) original location, (2) on a pallet truck, (3) on a different floor, and (4) back in original location). Moving the container to a different location resulted in an observable change to the top unit drive point FRF curves (0–200 Hz) leaving the upper frequency portion of the spectra, associated with identification, intact (200–1 kHz) (Figure 6). Although there were changes to the FRF curves of the base unit, the changes in the top unit FRF curves were more apparent. The container acts as a rigid body that pivots at the interface between the base unit and the floor; this leads to greater movement at the top of the container which is further away from the pivot point. Comparing the original location with attempts to replace the container in the same location, the GC analysis indicated a minor change with shape and amplitude correlations of 0.95 and 0.96 respectively. Confirmation of this result would therefore be reliant on the

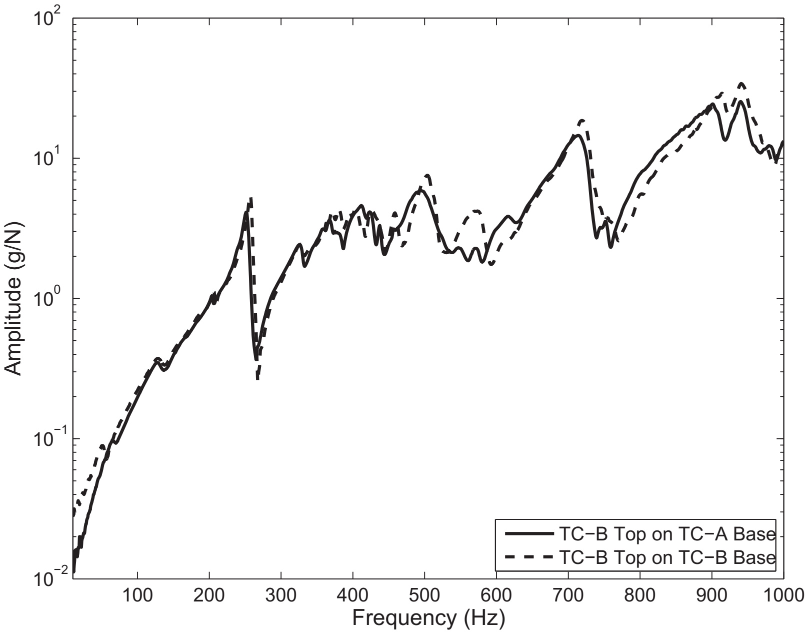

Figure 5: Example frequency response function spectra comparing TC-B (original configuration) with TC-B top unit on the TC-A base unit. These spectra were recorded from the base unit (response and excitation at position 7, axis X) (1 g = 9.81 ms^{-2}).

outputs from the one-to-one analysis and corroborating evidence from the rest of the chain of custody regime.

Tamper Experiments—Normal Points of Entry

These experiments investigated whether this technique could be used to tell if an unauthorized attempt had been made to access the container via the normal points of entry (i.e., the access door or the joint assembly). Both the access door and the joint assembly involved the use of bolts to complete the seal. The following configurations were measured:

- Access door: (1) original position, (2) off, (3) right-hand bolts only, (4) three bolts, and (5) repeat of original position.
- Bolted joint assembly: (1) bolts tightened to specification, (2) bolts loosened and re-tightened to specification, (3) bolts hand tightened, and (4) bolts tightened to specification but in a random order.

One-to-one analysis of the FRF spectra from the base unit showed significant difference for all the access door configurations (Figure 7). The drive point FRF nearest the access door provided the clearest differentiation. It

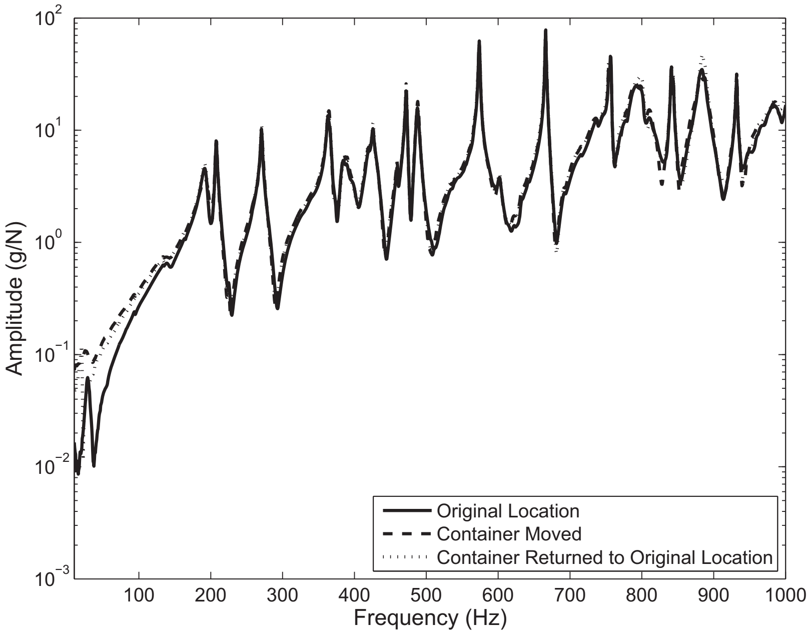

Figure 6: Tamper experiments, moving the container, three example frequency response function spectra (response and excitation at position 3, axis Y). Movement of the container seemed to have a greater effect on the lower frequency portion of the FRF curve (0–200 Hz) leaving the upper frequency portion of the spectra, associated with identification, intact (200–1 kHz) (1 g = 9.81 ms^{-2}).

was interesting that this technique could go some way towards recognizing such a subtle change in configuration. It was felt that this warranted further consideration and some additional experiments on this topic were performed which will be discussed later.

One-to-one analysis relating to the configuration of the bolted joint assembly between the top and base units (Figure 8) highlighted noteworthy differences in the FRF spectrum when comparing hand tightened bolts with torque wrench tightened bolts (i.e., to specification). Loosening and re-tightening the bolts to specification produced a less pronounced effect that registered as a minor change during GC analysis ($\chi_s = 0.94$; $\chi_a = 0.95$). As a minor change, this might be the result of operator or experimental factors.

Tamper Experiments—Tamper/Repair Experiments

The following tamper/repair experiments configurations were investigated:

- Damaged versus undamaged containers (holes in the base and top units with sizes ranging from approximately 5 mm to 20 mm).

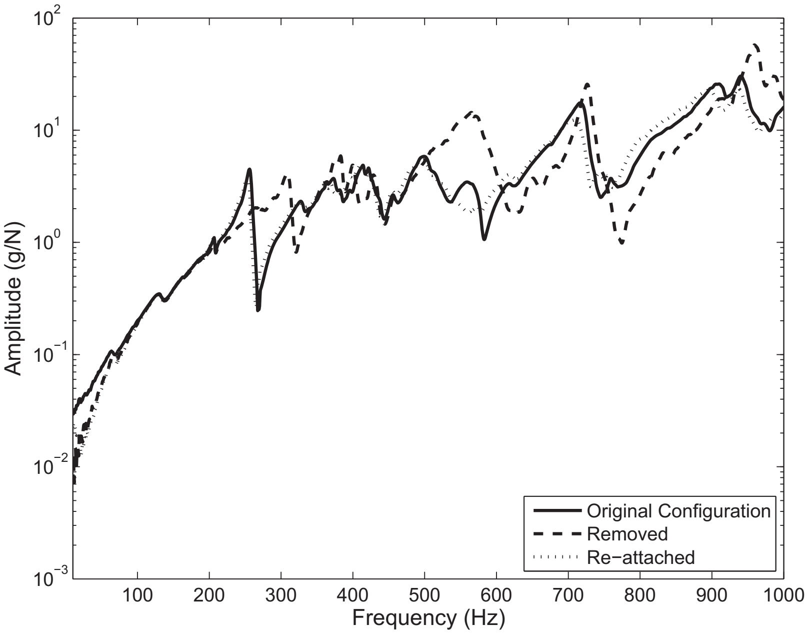

Figure 7: Tamper experiments, normal point of entry via the access panel, three example FRF spectra (response and excitation at position 7, axis X). These curves show three of the access door configurations: (1) original position, (2) off and (5) repeat of original position (1 g = 9.81 ms^{-2}).

- Comparison with a container that had been repaired by placing a lightweight gauze patch over the holes.

The damage to the container caused the loss of certain resonance peaks within the top unit FRF curves, particularly above 400Hz (Figure 9). The drive point FRF nearest the damage provided the clearest differentiation. It was noted that the stiffer, more highly damped, base unit provided less useful dynamic information than the top unit. Attempts to repair the damage also registered during the one-to-one analysis of the FRF responses (Figure 10); this was confirmed by a major change in the GC correlation coefficients ($\chi_s = 0.91$; $\chi_a = 0.93$). It was noted that:

- Ideally the measurements need to be taken at points close to the tamper.
- The stiffness and mass of the container will affect the ability of the technique to spot a change. Changes were less apparent in the stiffer, higher mass, base unit than in the top cover.
- The repair was a lightweight patch; other repair mechanisms would produce different results.

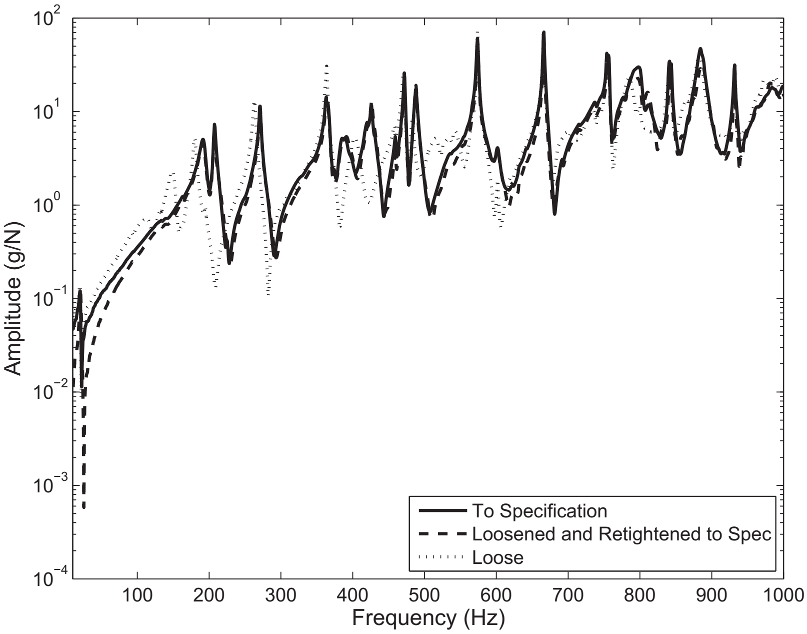

Figure 8: Tamper experiments, normal point of entry via the bolted joint assembly, three example FRF spectra (response and excitation at position 3, axis Y) (1 g = 9.81 ms^{-2}).

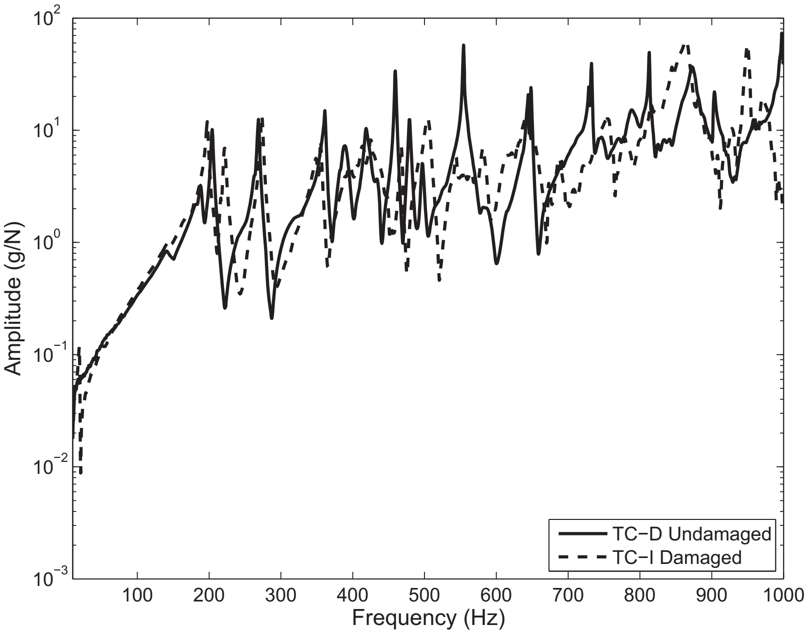

Figure 9: Tamper experiments, tamper/repair experiments, undamaged container compared with a damaged container, two example FRF spectra (response and excitation at position 3, axis Y) (1 g = 9.81 ms^{-2}).

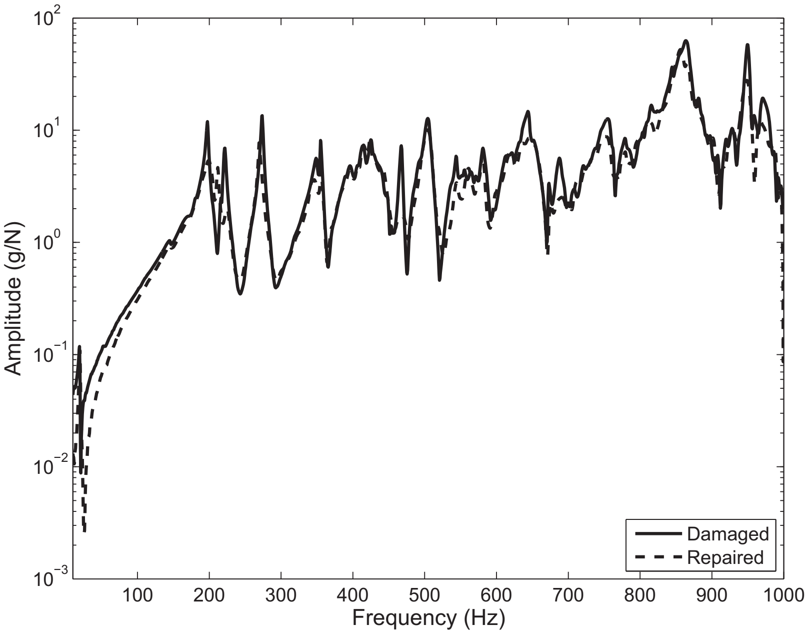

Figure 10: Tamper experiments, tamper/repair experiments, the effect of repairing the container, two example FRF spectra (response and excitation at position 3, axis Y) (1 g = 9.81 ms^{-2}).

- The ability of this technique to detect changes to the underside of the container was not tested during this experimental campaign.

Internal Configuration

The following internal configurations were tested:

- Full furniture without a test mass.
- Full furniture with a test mass.
- Partial furniture.
- No internal contents.

One-to-one analysis showed that changes in internal contents seemed to have a greater effect on the lower frequency portion of the FRF curve (0–200 Hz) leaving the upper frequency portion of the spectra, associated with identification, intact (200−1 kHz) (Figures 11 and 12). The technique identified a difference if a large change was made to the internal contents of the container, i.e., the addition of full furniture or the addition of a test mass. These large scale changes resulted in additional resonance peaks or troughs in the 0

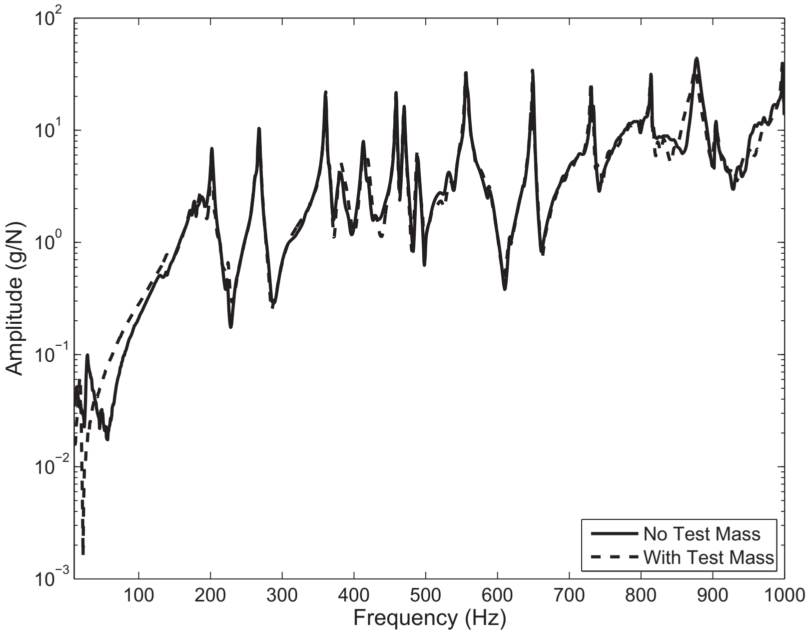

Figure 11: Example FRF spectra comparing a container (full furniture) with and without a test mass (response and excitation at position 3, axis Y). Changes in internal contents seemed to have a greater effect on the lower frequency portion of the FRF curve (0–200 Hz) leaving the upper frequency portion of the spectra, associated with identification, intact (200–1 kHz) (1 g = 9.81 ms^{-2}).

to 200 Hz range (Figures 11 and 12). GC analysis confirmed this observation, showing a major change in the correlation values when comparing a container with and without the test mass ($\chi_s = 0.90$; $\chi_a = 0.93$). Note that the internal features of the container were accessed by undoing the bolted joint assembly and removing the top unit; during reassembly the bolts were re-tightened to specification.

The one-to-one technique was not sensitive enough to detect a more subtle change where only part of the internal contents had been removed (Figure 12). Again this was confirmed by a GC comparison of full furniture versus partial furniture which yielded shape and amplitude correlations of 0.95 and 0.97 respectively; falling into the category of baseline/undetectable change. Further work is required to understand how sensitive this approach could be to internal configuration changes as this will be dependent on container design and the coupling between container and contents.

Data Analysis Methodology

Although one-to-one analysis is a simple, qualitative way to analyze the data, it has two disadvantages in this scenario:

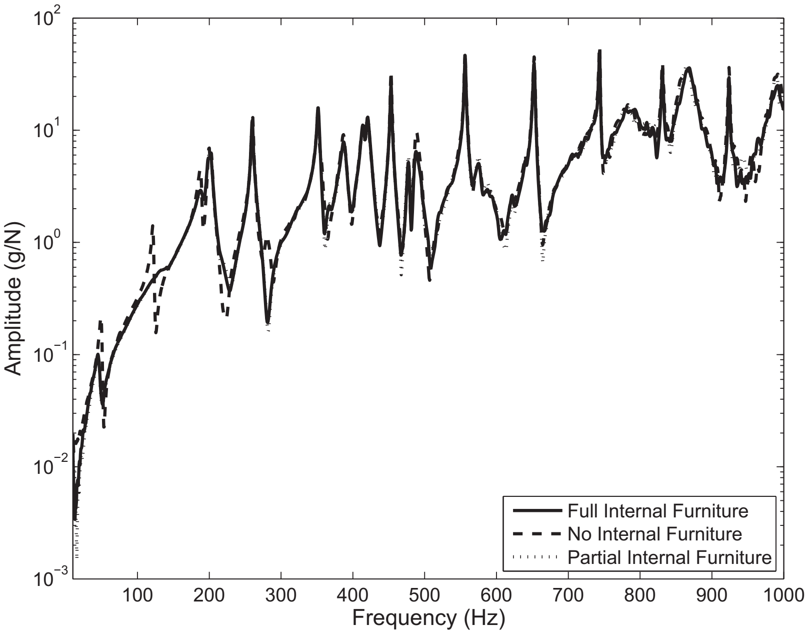

Figure 12: Example FRF spectra comparing a container (no test mass) with full furniture, partial furniture and no furniture (response and excitation at position 3, axis Y). Changes in internal contents seemed to have a greater effect on the lower frequency portion of the FRF curve (0–200 Hz) leaving the upper frequency portion of the spectra, associated with identification, intact (200–1 kHz) (1 g = 9.81 ms^{-2}).

- It requires a subjective judgment from a subject matter expert.
- It only uses a portion of the available dataset.

The GC analysis technique was only used on a sub-set of the experiments undertaken but it did demonstrate that it is possible to automate the analysis routine and utilize all the available data. The shape and amplitude correlation metrics provided a very good overall characterization of the structure and did not require personal judgment as to which FRFs are important. The ideal approach would be to use GC and one-to-one analysis in tandem, with the precise balance of techniques being determined on a case-by-case basis. GC analysis would provide the monitoring party with an initial indication of an anomaly and a classification of that result in terms of severity (for example, in this experiment the terms minor and major change were used). This would then be used to target monitoring party effort in evaluating that anomaly with one-to-one analysis and evidence from other elements within the chain of custody regime.

The GC technique utilized the full spectrum from 0 to 1 kHz, however some effects were only seen within certain regions of the curve. A region of interest (ROI) approach, segregating the spectrum into frequency bands, might provide increased sensitivity in terms of the classification of results, indicating not only a level of change but also where that change might have occurred. The integration of the approach with image correlation techniques might also provide increased capability, indicating which FRF spectra within a data set should be targeted for one-to-one analysis.

ADDITIONAL MEASUREMENTS

It was noted from previous experience that the re-assembly of a structure containing joints rarely yields the same overall FRF response. The experimental results from this trial demonstrated that this technique might detect a subtle change resulting from the re-assembly of a joint, even when there is an agreed assembly specification. It was postulated that this effect could be used when designing a tamper indicating container to ensure that the assembly operation would create a unique FRF fingerprint that could not be recreated. A small container was modified to support an initial experimental investigation. The container consisted of two parts; the main body and a lid with a rubber gasket. The lid and main body of the container were joined together using four bolts. The bolts allowed the joint, and the container as a whole, to be uniquely stressed by applying different torque configurations to the bolts.

A small number of FRFs were obtained using a lightweight modal hammer and a single axis accelerometer. The bolts were tightened to a torque of 2, 3, and 4 Nm respectively, and tested at each torque setting; results showed that the magnitude of the bolt torque significantly affects the FRF characteristics. The container was loosened, re-tightened and tested at each of the 2, 3, and 4 Nm bolt torque settings; this produced a change in the FRF spectrum. This showed that it is possible to determine if the container had been opened, especially for lower torque configurations.

CONCLUSIONS

The purpose of this project was to assess whether a modal testing technique could be used within a chain of custody deployed as part of a possible future monitored nuclear weapon dismantlement regime. It was proposed that the technique would be used as a signature tracking method. Vibration frequency response functions spectra would be recorded before and after a containerized TAI was taken into storage or through a transport phase. A comparison of these data sets would then indicate if an unauthorized change to the container or containerized object had occurred.

A preliminary experimental campaign was completed which investigated the suitability of the technique in terms of deployment, repeatability, unique identification, detection of tampering with the container and detection of internal configuration changes. To support the campaign a simulant container/object system was utilized and an optimized modal testing set-up was devised. The deployed technique included the use of a calibrated modal hammer (excitation measurement) and tri-axial accelerometers (response measurement). The data analysis phase included an analytical method for classifying the results to support a judgment by the operator on whether a significant alteration had occurred within the container/object assembly.

The following conclusions, mapped to the original aims of the experimental campaign, can be drawn:

Deployment: Overall it was felt that it would be feasible to deploy this technique within a monitoring regime. A subject matter expert was required to design the experiment and undertake the initial set-up (careful design at this stage is key to the success of the modal testing approach). The final set-up was found to be fast, robust, portable, and easy to deploy by multiple monitoring teams. The testing routine could be performed after only a few hours of training; detailed data analysis would be performed by an experienced operator.

Data Analysis Approach: The tandem approach of one-to-one and GC analysis seemed to provide a good balance of subjective operator assessment and independent automated data analysis. The GC analysis provided a way of classifying the results in terms of “severity”; this could potentially help the monitoring team to effectively target any subsequent investigation.

Repeatability: The experiment was repeatable and independent of operator, both in terms of marking out the measurement locations and in undertaking the measurement routine.

Unique Identification: The technique uniquely indentified each container within the given sample set; attempts to swap components were also identified by the system.

Tamper Indication: A movement of the container to and from given locations was reflected as observable changes in the measured response. This indicator was in the lower portion of the measured spectra which left the ‘unique identifier’ portion of the signature intact. The experiments demonstrated that the technique might detect the subtle changes that can occur when a jointed structure is un-bolted and then re-sealed, even when it is re-assembled according to an agreed specification. Damaged and repaired containers were measured and this showed that this technique might be able to detect an unauthorized attempt to access the container by cutting through the boundary.

Internal Configuration: The technique detected that an object had been placed within the container and any large scale change to the internal configuration.

In conclusion, this modal testing technique has potential as a chain of custody signature tracking tool in that it uniquely identified the given containers, provided a level of tamper indication and could be deployable in this kind of regime. However, further work would be required to fully explore how this technique could be used. The success of the technique, particularly with tamper indication, was dependant on the size and construction of the container and the positioning of the measurement locations. The selection of measurement locations during this trial was based on expert judgment coupled with a level of knowledge of the container design. The host may not be prepared to discuss container design; under these circumstances it may be difficult for the monitoring party to assess the effectiveness of the modal testing approach. Nevertheless, there is a potential application where the container has been specifically designed for the regime or the container design details are open to both parties. Note that in situations where the full container design is disclosed it might be possible to use analytical models to optimize the experimental set-up.

Given the above, potential future work in this area would include the following:

- The technique needs to be tested for susceptibility to environmental factors (i.e., temperature).
- The expansion of the unique identification experiments to include a larger sample set and differing container types.
- A more detailed investigation of tamper indicating properties including a consideration of differing repair mechanisms, size of tamper, and the location of the tamper on the container.
- An investigation of the sensitivity of this technique to internal configuration changes. This additional work would also allow for a full assessment of whether an information barrier is required when fielding this technique.
- Further consideration of potentially additive effects involving multiple simultaneous tamper and experimental factors.
- Improvements to the GC analysis and classification approach to further highlight and categorize anomalies. This could include the use of regions of interest and image correlation techniques.
- Research into “designer containers” which incorporate joints with enhanced tamper indicating properties.

For all monitoring techniques deployed within this scenario, it is important to consider how the host and monitoring parties could obtain, and maintain, mutual trust in the deployed equipment (i.e., authentication and certification). Future work on modal testing would need to investigate how authentication and certification of the system would be achieved.

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