ISSUES IN MULTI-REFERENCE IMPACT TESTING OF STEEL-STRINGER BRIDGES

M. Lenett, N. Catbas, V. Hunt, A. E. Aktan, A. Helmicki, and D. Brown

University of Cincinnati Infrastructure Institute
741 Baldwin Hall, ML71
Cincinnati, OH 45221

ABSTRACT. A recommended methodology is presented for the condition assessment and structural evaluation of a highway bridge. Based upon the structural identification concept, this global NDE method employs the modal test technique of multiple reference impact testing as its principle experimental tool. Modal flexibility provides a conceptual, quantitative, comprehensive and damage-sensitive signature for the structure. A research project is underway to rigorously demonstrate and verify these experimental concepts and tools. A typical steel-stringer bridge will be subjected to a series of deliberately induced damage, simulating typical deterioration and damage scenarios which may affect steel-stringer bridges. For the baseline and subsequent damage scenarios, issues which may cause multi-reference impact testing to be an impractical experimental tool for bridge evaluation are identified and investigated. Quality control strategies which are intended to minimize experimental errors are developed and investigated as well.

1. INTRODUCTION

A global NDE method, based on the structural identification concept, has been developed using the methods of multi-reference impact testing as the experimental foundation. The data acquired through this experimental technique is transformed to modal flexibility, which has been demonstrated to be a conceptual, quantitative, comprehensive, and damage-sensitive signature [Ref. 1]. Flexibility also provides a conceptual condition index, since it may be used to conveniently obtain the deflected shapes of a bridge under any loading pattern. A research project is underway to rigorously demonstrate that both multi-reference impact testing and modal flexibility are valid and effective tools for the condition assessment and evaluation of steel-stringer bridges, which may be possibly affected by any level of hidden deterioration or damage. However, in order to ensure a structurally relevant modal flexibility, the bridge itself, and thus the experimental data acquired through multi-reference impact testing, must satisfy the fundamental requirements of modal analysis. Examples of impact data acquired throughout the current project are used within this paper to illustrate the fundamental requirements, various issues, and quality control strategies associated with multi-reference impact testing of a steel-stringer bridge.

2. BASIC ISSUES

A “typical” steel-stringer bridge located in Cincinnati (HAM-561-0683, Figure 1) is the subject of the ongoing research project. As with any structure subjected to the methods of modal analysis, this bridge, as well as other steel-stringer bridges, must satisfy three behavioral assumptions which are fundamental requirements of modal analysis: Linearity, Observability, and Time-Invariance.

A typical steel-stringer bridge is continuously subjected to variable environmental conditions (temperature, humidity, etc.) and consists of steel, concrete, and often an asphalt overlay on top of the reinforced concrete deck. Essentially, concrete and asphalt are nonlinear structural materials. In addition, their stiffness, as is steel’s, is a temperature dependent property. Hence, the fundamental assumptions of linearity and time-invariance are critical issues. Modal analysis is not applicable to a steel-stringer bridge system if these issues cannot be resolved.

2.1 Linearity

As shown in Figure 1, HAM-561-0683 possesses an asphalt overlay. FRF’s generated by measuring both a vertical impact force and vertical acceleration on the asphalt overlay can be used within Maxwell-Betti’s principle of reciprocity ($H_{pq} = H_{qp}$) to determine whether the asphalt invalidates the linearity assumption of modal analysis. In other words, reciprocity can be used to evaluate whether time and termperature prevent the use of asphalt as a measurement base throughout multi-reference impact testing. Figure 2 displays reciprocity between two FRF’s generated from ashpalt-based impact and acceleration measurements. This figure reveals magnitude reciprocity that sufficiently satisfies Maxwell-Betti’s principle for a linear system. Phase reciprocity is verified as well but is not displayed.

Figure 3 displays reasonable reciprocity between FRF's developed through concrete-asphalt measurements (i.e. impact on concrete, acceleration on asphalt and vice versa). The reciprocity displayed within Figures 2 and 3 is typical of the data acquired throughout this project. Such reciprocity implies that a steel-stringer bridge may be interpreted as a linear system. Hence, the presence of concrete and asphalt within the structural system does not invalidate the linearity assumption of modal analysis.

Impacting the bridge at different levels of force is another method of verifying structural linearity. For a linear system, increasing the level of applied force will proportionally increase the level of direct response. Defining an FRF as a simple ratio between response and applied force (X/F) yields the following relationship for a linear system:

For applied force F, response is $X \Rightarrow H = X/F$

For force 2F, response is $2X \Rightarrow H=2X/2F=X/F$

Hence, for any particular response location on a linear system, the same FRF should be acquired for different input (force) levels (as long as the applied force does not exceed the linear range of the structure). The FRF's presented in Figure 4 verify this and thus provide further evidence that the investigated bridge system is linear.

2.2 Time-Invariance

As stated earlier, steel, concrete, and asphalt are materials whose stiffness is temperature dependent. Thus, if temperature varies over time, any structure comprised of these materials, such as a steel-stringer bridge, would not be time-invariant. As part of this research project, time invariance was investigated by repeatedly performing sine sweeps of short time duration. Sweeps involving different frequency bandwidths were repeated several times a day so that the effects of temperature fluctuations could be observed. The investigative results for a 10.5 - 13.0 Hz bandwidth at particular bridge locations are presented in Figure 4 which reveals the nonstationary nature (i.e. time variant behavior) of this typical steel-stringer bridge. The extent of nonstationarity varies as a function of bridge span location and frequency bandwidth.

A rigorous multi-reference impact test conducted over the same time period as the sweeps of Figure 5 would incorporate into the acquired data the nonstationary nature of the bridge. The structural parameters that are to be estimated from the data would therefore vary with time. Many post-processing algorithms, particularly time domain algorithms such as PTD, have difficulty interpreting time-varying data. Hence, a unique impact test procedure is needed which minimizes and helps control nonstationary aspects of the bridge.

Figure 6 displays an extensive accelerometer layout used in conjunction with several impact points. For a system that satisfies linearity, utilizing such a test grid will significantly reduce the time duration of an impact test. This may be attributed to the principle of reciprocity, which essentially defines unmeasured FRF's from measured ones. Reducing the length of a test minimizes possible variations in temperature, humidity, and other environmental conditions which may alter bridge behavior. In addition, environmental conditions vary with the time of day (Figure 7). A test performed in the early morning hours will experience less temperature variation than one conducted in the late morning-early afternoon. In essence, testing at a particular time of day and the use of an optimum grid will permit the investigated bridge to be modelled as a time-invariant system.

3. QUALITY CONTROL

After verifying that the investigated bridge satisfies the linearity and time-invariant assumptions of modal analysis, further impact tests can be conducted. As previously indicated, the data acquired through these impact tests will be used to define the modal flexibility of the bridge. Thus, the acquired data must be of as high quality as possible. For each impact test conducted, a set of quality control checks has been established in order to ensure that (a) linearity and time-invariance are satisfied; and (b) the data is not corrupted by variance (electronic noise) and bias (aliasing, leakage, clipping, calibration, etc.) type errors. The various quality control categories associated with impact testing a steel-stringer bridge are:

(1) Temperature Control
Test during a time period of constant temperature or minimal temperature variation. This helps ensure satisfaction of the time-invariance assumption.

(2) Data acquisition settings
Proper data acquisition settings will minimize aliasing and leakage errors and improve signal to noise ratios. Pertinent data acquisition settings are:
(a) Frequency bandwidth and resolution
•Sufficient resolution minimizes leakage errors; Maximum frequency of interest is used by some systems to define sampling frequency.
(b) Force,Exponential Windows
•Applied to time domain signals to satisfy FFT requirements; will also reduce noise level in time signals thus improving signal to noise ratios.
(c) Number of Averages
•Five averages are used to minimize errors introduced by unnmeasured and undesirable sources of excitation (i.e. truck traffic, wind).

(3) Signal to Noise ratios
Signal quality should be improved at the expense of noise content by applying time domain windows and external

gains to incoming time signals in order to improve signal quality at the expense of noise content.

(4).Hammer characteristics
The hammer supplies the "impulse" force excitation that is required throughout multi-reference impact testing. It must generate sufficient energy and force to excite the modes that are needed for computation of modal flexibility which, for a typical steel-stringer bridge as observed through this and previous research, are within a bandwidth of 5-30 Hz [Ref. 3, 4, 5, 6g]. The proper combination of the following characteristics can achieve the necessary energy levels:

(a) Mass of hammer (i.e. weight on drop hammer)
(b) Tip stiffness
(c) Drop height (for drop hammer)

(5) Impact when there is no traffic on or below bridge.
For the purpose of impact testing, this minimizes unwanted responses due to unmeasured traffic excitation.

(6) Raw Time Data Check
Viewing raw time histories permits direct observation of line errors, improper sensor mountings, improper window settings, and inadequate voltage ranges.

(7) FRF checks
(a) Observe Input Power Spectrum
•Describes for each frequency within the bandwidth of interest the energy that has been input into the bridge system. In addition, permits detection of 10-20 dB dropoff in input energy.
(b) Observe Coherence functions
•Coherence provides a "measure" of how much the response at a particular position (output) is due to the applied impact (input).
(c) Check reciprocity and stationarity throughout test.
•Ensure that linearity and time-invariance are sufficiently satisfied.

(8) Sensor Error Strategies
Recalibrations before and after a test and in-test checks such as reciprocity help certify that all pertinent test sensors are properly functioning.

The rigorous use of these checks has revealed blatant instrumentation and data acquisition errors throughout the data acquisition stage. Such errors have included faulty microdot and BNC cables, improper accelerometer mounting (accelerometer not rigidly bonded to bridge deck), damaged accelerometers, and responses on the bridge deck due to truck traffic below the bridge. Figure 8 is an example of an instrumentation error and displays reciprocity involving a bad accelerometer. The use of reciprocity as an in-test check can reveal a sensor error which permits, if there are additional accelerometers, replacement of the bad sensor and a retest. In general, these quality control checks are intended to minimize experimental errors prior to flexibility computation.

4. CONCLUSION

It is believed that the issues and strategies presented within this paper are applicable to all steel-stringer bridges. A practical impact test method which incorporates these various issues and strategies must be developed if multi-reference impact testing is to be used as the principle experimental tool for the condition assessment and structural evaluation of steel-stringer bridges (as well as other bridge types). This research project is the first "step" toward the development of a practical test method. It has revealed issues of practical concern (ranging from cable and sensor mounting problems to time of day and duration of test) yet has also verified that the experimental data acquired through impact testing can be used to identify induced damage scenarios. In other words, modal flexibility computed from the acquired data has yielded reliable results for condition assessment. Essentially, the use of multi-reference impact testing for purposes of condition assessment has been validated. The challenge now is to develop from the various test issues and quality control strategies a practical bridge evaluation and inspection test method.

5. ACKNOWLEDGMENTS

A peer review panel has been formed for the current project: Drs. Brown, SDRL, University of Cincinnati; Cantieni, EMPA, Switzerland; Ewins, Imperial College, UK; Farrar, Los Alamos National Labs; Rubin, Aerospace Corporation; and Yao, Texas A&M. Their recent workshop, invaluable advice, and future collaboration have brought international recognition to this research and assured the successful attainment of the project goals.

This research is supported by the Ohio Department of Transportation, Research and Development, and the FHWA through the HPR Program. Mr. Edwards, Hanhilammi, Barnhart, Welker, and Eltzroth of ODOT and Mr. Shamis of Ohio FHWA have extended their confidence and support for which we are grateful. We also acknowledge the valuable input provided by Dr. Chase of FHWA Headquarters and the Office of Research at Washington, D.C.

6. REFERENCES

1. Rubin, S., and Coppolino, R. (1983). *Flexibility Monitoring Evaluation Study,* Minerals Management Service, U.S. Department of the Interior, Washington, D.C.

2. Allemang, R.J. (1990). "Vibrations: Experimental Modal Analysis," *UC-SDRL-CN-20-263-662*,). Structural Dynamics Research Lab., University of Cincinnati, OH..
3. Aktan, A.E., Chuntavan, C., Lee, K.L., and Farhey, D.N. (1994). "Nondestructive Testing and Identification for Bridge Rating, Phase 2: Steel-Stringer Bridges." FHWA, *Report FHWA/OH-95/021*, Washington, D.C., April.
4. Aktan, A.E., Lee, K.L., Chuntavan, C., and Aksel, T. (1994). "Modal Testing for Structural Identification and Condition Assessment of Constructed Facilities." Proc., *International Modal Analysis Conference 12,* Honolulu, HI, pp. 462-468.
5. Toksoy, T., and Aktan, A.E. (1993). "Bridge Condition Assessment by Modal Flexibility." Proceedings, *International Conference on Nondestructive Testing on Concrete in the Infrastructure*, Dearborn, Michigan, Society for Experimental Mechanics, June, pp. 21-39.
6. Aktan, A.E., Farhey, D.N., and Dalal, V. (1995). "Issues in Rating Steel-Stringer Bridges." *Transportation Research Record 1476*, TRB, National Research Council, Washington, D.C.

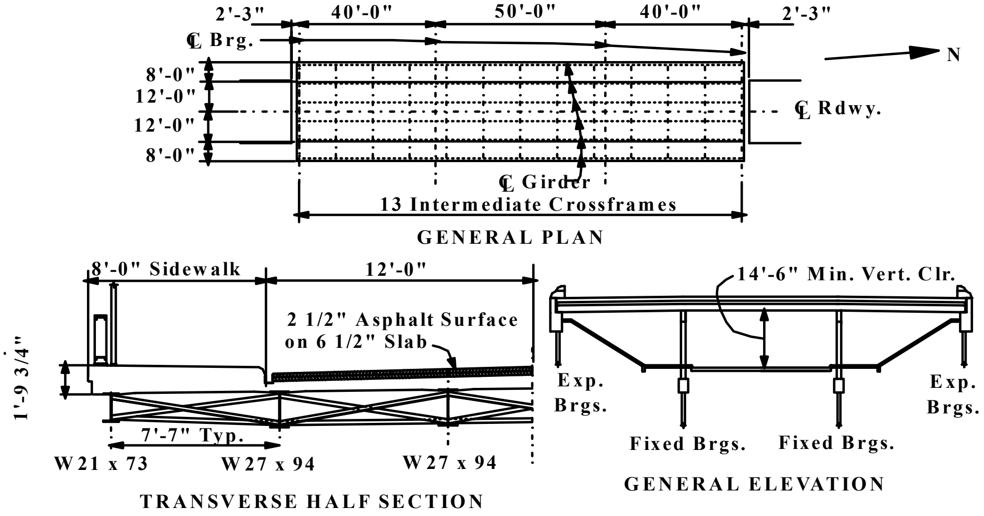

Figure 1 : HAM-561-0683 Pertinent Dimensions

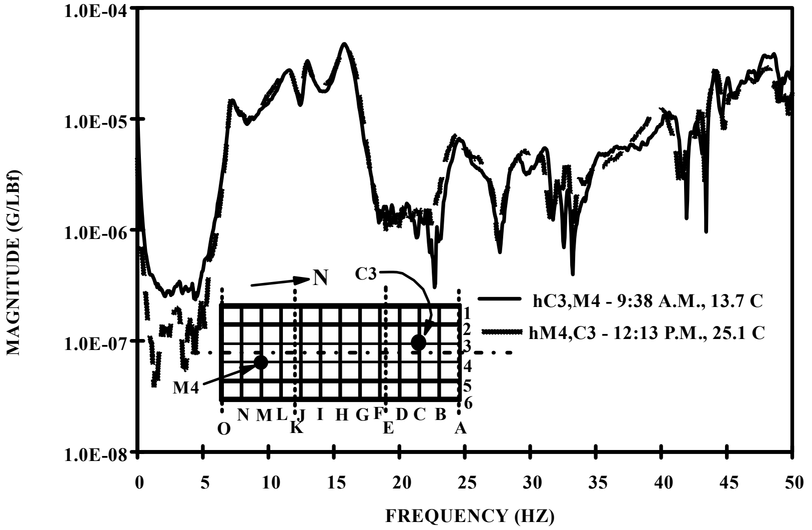

Figure 2: Reciprocity due to impact-response measurements on asphalt overlay

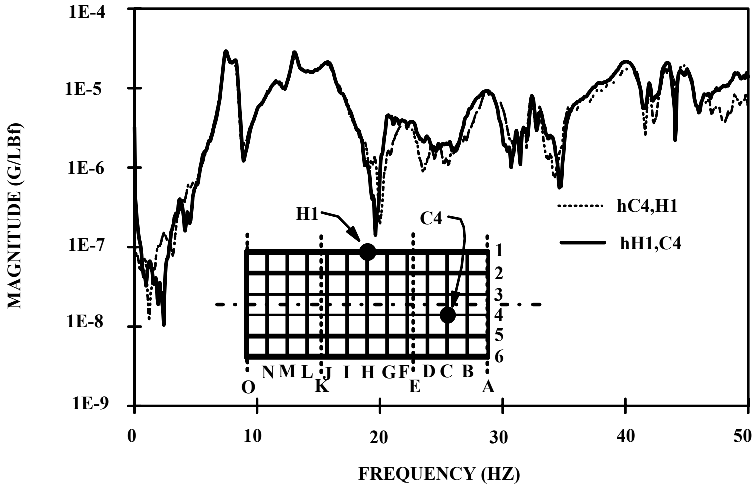

Figure 3 : Reciprocity - Asphalt Overlay vs. Concrete Deck

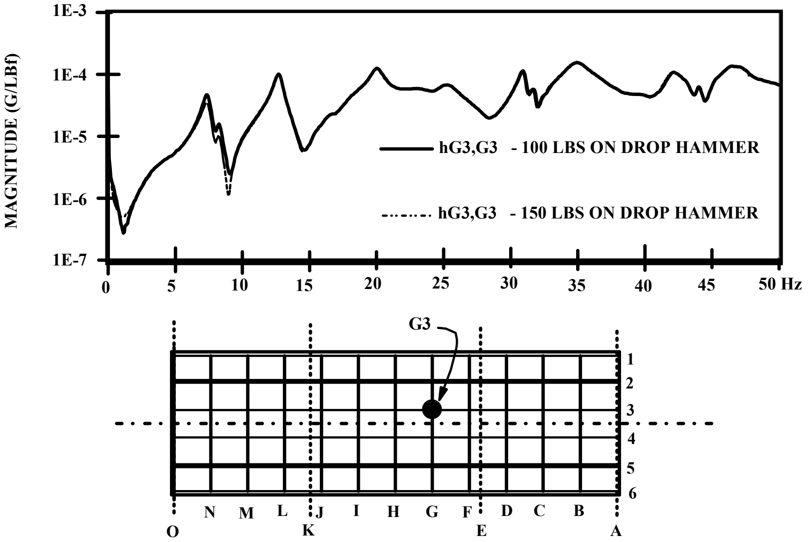

Figure 4 : Structural Linearity Check using Constant Height w/ varying weight on Drop Hammer

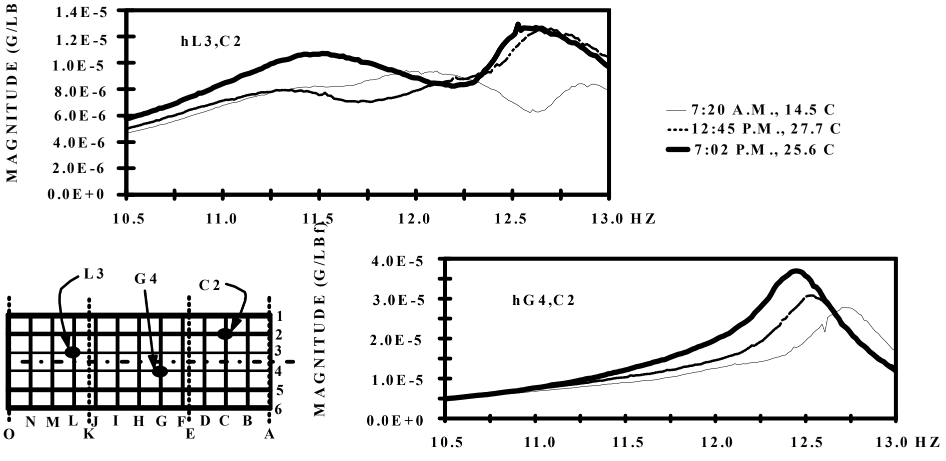

Figure 5 : Nonstationary (Time-Variant) Behavior

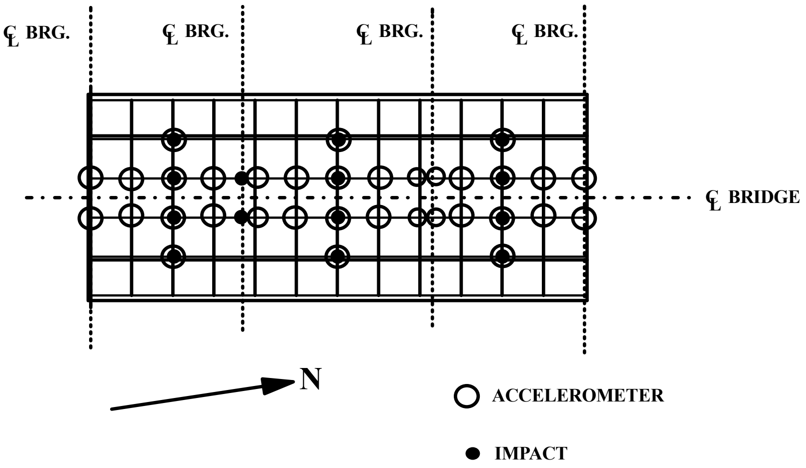

Figure 6 : Modal Test Grid

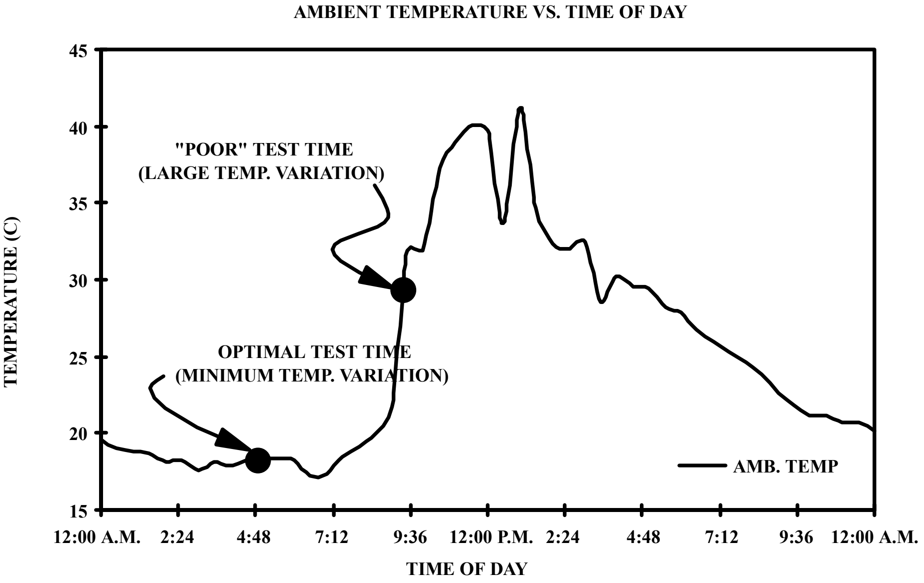

Figure 7 : Temperature Variations with Time of Day (for 8/1/96)

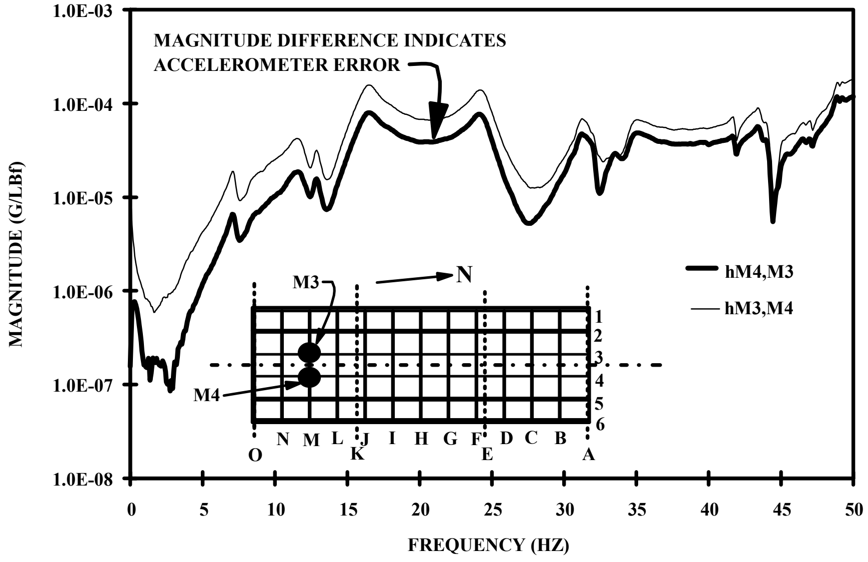

Figure 8 : In-Test Reciprocity Check revealing faulty accelerometer at M4