

PERFORMING BRIDGE CONDITION ASSESSMENT WITH SPliced MULTI-REFERENCE IMPACT DATA

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ABSTRACT

A unique impact test procedure, referred to as “rapid” multi-reference impact testing, has been developed through research on decommissioned and commissioned steel-stringer bridges. This same research has also demonstrated that a reliable measure of in-situ flexibility can be computed from the modal data acquired through such a method. However, the research performed on these respective bridges focused on testing only one traffic lane. A more comprehensive flexibility matrix of a bridge’s superstructure could be generated if information for multiple lanes is acquired. Such a flexibility matrix would enhance condition assessment of the bridge superstructure and help with predicting superstructure response to multiple lane and truck loads. However, due to typical traffic requirements, at least one lane of a bridge must remain open, thus prohibiting a full impact test of the bridge. To accommodate such conditions, lane-by-lane impact tests should be performed and the identified modal results of the respective tests (eigenvalues, eigenvectors, scaling) linked, or spliced, together. These spliced results could then be used to define a multiple-lane flexibility matrix of the bridge superstructure. Within this paper, the authors will discuss how, on commissioned steel-stringer bridges, “rapid” multi-reference impact tests were performed on a lane-by-lane basis, how the identified modal results from different lane tests were spliced together, and how a multiple-lane flexibility was computed from the spliced results.

NOMENCLATURE

$[H(\omega)]$	FRF matrix
$[K]$	stiffness matrix
$[f]$	flexibility matrix
$\{\psi\}_r$	r^{th} modal vector
$\{\psi\}_r^T$	transpose of r^{th} mode
$\{\psi\}_r^*$	complex conjugate of r^{th} mode

$\{\psi\}_r^{*T}$	Hermitian of r^{th} mode
λ_r	r^{th} eigenvalue ($=\sigma_r + j\omega_r$)
M_{Ar}	Modal A (scaling) for r^{th} mode
$\{\psi\}_r^{\text{Region1}}$	r^{th} modal vector from Region 1
$\{\bar{Y}\}_r^{\text{Region1}}$	spatially common modal vector coefficients
a	alpha coefficient
$\{\bar{Y}\}_r^{\text{Region1}T}$	transpose of spatially common modal vector coefficients
$\{\bar{Y}\}_r^{\text{Region1}*}$	conjugate of spatially common modal vector coefficients
$\lambda_r^{\text{Region1}}$	r^{th} eigenvalue from Region 1
M_{Ar}^{Region1}	Modal A (scaling) for r^{th} mode from Region 1
$\{\psi\}_r^{\text{comprehensive}}$	spliced modal vector
$\lambda_r^{\text{comprehensive}}$	eigenvalue for spliced modal vector
$M_{Ar}^{\text{comprehensive}}$	scaling for spliced modal vector

1. INTRODUCTION

Research on decommissioned and commissioned reinforced concrete deck on steel-girder bridges (i.e., steel-stringer bridges) has led to the development of “rapid” multi-reference impact testing [1,2], a unique impact test procedure for civil infrastructure that involves:

- 1) selecting the girderlines of a bridge superstructure along which flexibility is desired;
- 2) positioning accelerometers on the upper-side of the bridge deck directly above all girder-crossframe intersections and girder-bearing positions associated with the selected girders; and;
- 3) impacting at a select number of these accelerometer positions.

An example of a “rapid” multi-reference impact test grid that was developed in the manner described above is presented in Figure 1. Through these same research efforts, it was also demonstrated that an accurate and reliable

measure of in-situ flexibility could be obtained for the tested region of the superstructure from acquired “rapid” multi-reference impact test data [2,3,4]. The structural accuracy and relevancy of the flexibility was evaluated by comparing measured truck-load displacements with flexibility-derived (simulated) truck-load displacements (refer to Figure 2).

Up to this point, “rapid” multi-reference impact testing of a commissioned steel-stringer bridge has involved only one traffic lane on the bridge. This is due to Ohio Department of Transportation traffic control requirements. On a commissioned bridge, the Ohio DOT requires that a bridge remain open to vehicles during inspections and repair/retrofit work. Consequently, it is often the case that one lane is closed to traffic. The resulting measure of flexibility obtained for this tested, or closed, lane can subsequently be used for the health monitoring/condition assessment of this particular portion of the bridge superstructure [2,3,4,5]. Furthermore, for truck loads positioned within the tested lane, the flexibility can be used to predict the live load response (displacements) of this portion of superstructure. However, if the response of the superstructure to multiple lane loadings (i.e., trucks in multiple lanes) is desired or if an overall 3D finite element model of a bridge is to be calibrated using an in-situ measure of flexibility, then a more comprehensive flexibility matrix – one that encompasses multiple lanes or a larger portion of the bridge superstructure (see Figure 3) – will be needed. This paper discusses experimental modal methods as well as modal data processing techniques that can be used to establish this multiple lane, or comprehensive, flexibility matrix.

2. SPLICING TECHNIQUES

To acquire, or define, a flexibility matrix for multiple bridge lanes, yet still comply with Ohio DOT traffic control requirements, a “rapid” multi-reference impact test should be performed in each lane of interest, one lane at a time. After completion of the individual lane tests, the multiple lane flexibility matrix may be established by (a) identifying the modal parameters – eigenvalues (λ_r), eigenvectors $\{\psi\}_r$, scaling ($M_{A,r}$) –for each respective lane, (b) link, or splice, these individual lane parameters into one comprehensive set of modal parameters (which identifies the dynamic characteristics of the multiple lane system), and (c) use the comprehensive set of modal parameters to define the in-situ comprehensive, or multiple lane, flexibility. Each of these steps is discussed within this paper, starting with splice techniques. Note that being familiar with the splicing method prior to actual field testing will provide insight on how to define and coordinate the test layouts within the individual lanes of interest.

The particular splicing method utilized throughout this bridge research was developed by Brown and colleagues at the University of Cincinnati Structural Dynamics Research

Laboratory (UC-SDRL) [6]. To facilitate the discussion of this method, assume that two different regions on the same system (i.e., structure), referred to as Region 1 and Region 2, have been impact tested. Several measurement points used in the test layout for Region 1 have also been used in the layout for Region 2. Modes identified from Region 1 and Region 2 test data will therefore possess several modal vector coefficients that correspond to the same spatial locations. These common coefficients are referred to as $\{\bar{y}\}_r$.

Modal Assurance Criterion (MAC) values indicate which modes identified from Regions 1 and 2 are similar to one another. A high MAC value ($MAC > 0.9$) between an identified mode from Region 1 and an identified mode from Region 2 implies that these modes define the same system mode. These two identified modes are therefore spliced together to define the overall system mode. The spatially common coefficients between these corresponding, or similar, modes are needed to initiate the splicing process. However, measurement errors, such as signal noise, during the impact testing of Region 1 and/or Region 2 may have caused differences amongst the spatially common modal vector coefficients. In other words,

$\{\bar{y}\}_r^{Region1} \neq \{\bar{y}\}_r^{Region2}$. Because of these errors and inequalities, splicing cannot be as simple as placing Region 2 modal vector coefficients into the Region 1 mode, or vice versa. The errors/inequalities that exist amongst the two sets of spatially common modal vector coefficients must first be minimized. To do this, a scalar quantity a is used to establish a linear relationship between the spatially common coefficients. This linear relationship may be expressed as:

$$\{\bar{y}\}_r^{Region1} = a \{\bar{y}\}_r^{Region2} \quad (1)$$

$\{\bar{y}\}_r^{Region1}$ is considered the *Master* set of modal coefficients and $\{\bar{y}\}_r^{Region2}$ is the *Slave* set. Consequently, $\{\psi\}_r^{Region1}$ is the *Master* mode and $\{\psi\}_r^{Region2}$ is the *Slave* mode.

Through least squares approximation methods, a may be computed as:

$$a = \frac{\{\bar{y}\}_r^{Region1}}{\{\bar{y}\}_r^{Region2}} = \frac{G \{\bar{y}\}_r^{Region1} \{\bar{y}\}_r^{Region2}}{G \{\bar{y}\}_r^{Region2} \{\bar{y}\}_r^{Region2}}$$

$$a = \frac{\{\bar{y}\}_r^{Region1T} \{\bar{y}\}_r^{Region2*}}{\{\bar{y}\}_r^{Region2T} \{\bar{y}\}_r^{Region2*}} \quad (2)$$

All modal coefficients in the *Slave* mode, $\{\psi\}_r^{Region2}$, are multiplied with a which scales all *Slave* mode coefficients to those in the *Master* mode, $\{\psi\}_r^{Region1}$. A comprehensive, or multiple region, modal vector can now be defined by taking

scaled modal coefficients at spatial locations only in Region 2 (these are scaled *Slave* modal coefficients) and placing them in the modal vector for Region 1 (the *Master* mode). In mathematical terms, this resulting comprehensive modal vector may be represented as:

$$\{\mathbf{y}\}_{r, \text{comprehensive}} = \left\{ \frac{\{\mathbf{y}\}_r^{\text{only_Region1}}}{\{\mathbf{y}\}_r^{\text{Region1}}} \right\} = \left\{ \frac{\{\mathbf{y}\}_r^{\text{Region1}}}{\mathbf{a}\{\mathbf{y}\}_r^{\text{only_Region2}}} \right\}$$

Because the modal coefficients in the *Slave* mode were scaled to the coefficients in the *Master* mode, the eigenvalue, λ_r , and modal scaling, M_{Ar} , associated with the *Master* mode are used for the comprehensive modal vector. With respect to the discussion in this paper:

$$\lambda_{r, \text{comprehensive}} = \lambda_r^{\text{Region1}} \text{ and } M_{Ar, \text{comprehensive}} = M_{Ar}^{\text{Region1}}.$$

3. TEST BRIDGE AND DEVELOPMENT OF TEST LAYOUT

One of six commissioned steel-stringer bridges carrying two lanes of traffic and recently subjected to a series of impact tests is presented in Figure 4. An accurate measure of the superstructure (deck and girder) flexibility associated with the two lanes is the desired test result. However, for this bridge, impact tests cannot be performed in both lanes simultaneously – as previously discussed, the Ohio DOT requires that one lane remain open on the bridge. Consequently, a “rapid” multi-reference impact test will have to be performed in a single lane when closed to traffic. Modal parameters identified for each lane will subsequently be spliced using the methods discussed in Section 2. Because Girder 3 is positioned directly beneath the boundary of the two traffic lanes (see Figure 4), locations on the bridge deck coinciding with the centerline of this girder serve as the common points needed for splicing the individual lane results. “Rapid” multi-reference impact test grids for both lanes therefore use coincident Girder 3 locations in their respective layouts. These layouts are displayed in Figure 5.

4. TEST EXECUTION

Throughout the duration of impact testing, it is desirable that all measured bridge response be due to the applied impact (impulse) force. Thus, to properly perform rigorous, “rapid” multi-reference impact tests in each lane and minimize unwanted responses due to unmeasured traffic excitation, impact force should be applied when there is no traffic on the bridge. To accomplish this, the Ohio DOT provided flagmen who controlled traffic flow in the open lane. For periods of 5 – 10 minutes, the flagmen would stop all traffic and prevent it from entering the open lane, thus making the bridge traffic-free for this period of time. The test crew therefore had a 5 – 10 minute interval to apply five impacts at one location (see Table 1 for this and other pertinent data acquisition parameters) and acquire high

quality averaged FRF data. As seen in Figure 5, each lane test used six different locations for impact application. With the aid of the Ohio DOT flagmen, all required impact within a lane was applied – and the “rapid” multi-reference impact test of that lane completed – in approximately one hour. Closure, test setup, and testing of the second lane immediately commenced following completion of the first lane test. The time required to perform “rapid” multi-reference impact tests in both lanes, which involved setup, execution, and teardown in each lane, was approximately six hours. This field test duration is well within the time-constraint of the typical Ohio DOT 8-hour working day.

Frequency Bandwidth	0 – 50 Hz
Frequency Resolution	0.0625 Hz
Coupling	AC
Voltage (ADC) range	± 100 mV to ± 2 V
Trigger Setting	10% of hammer voltage range
Windows	Force Window Width = 0.16 sec Exp. Time Constant, $\tau = 2$ sec
Number of Averages	Five

Table 1 – Pertinent Data Acquisition Parameters

5. IDENTIFIED MODAL PARAMETERS

Modal parameters - λ_r , $\{\psi\}_r$, and M_{Ar} – were identified for each lane from the test data acquired during individual lane tests. Figure 6 displays the first three modes identified for each lane. After identification, the respective modal parameters for a particular lane were used to estimate the flexibility of the lane (i.e., that particular portion of superstructure) according to the following equations:

$$[H(\omega = 0)] = \frac{1}{[K]} = [f] = \text{flexibility} \quad (3)$$

$$[f] = \sum_{r=1}^N \left[\frac{\{\mathbf{y}\}_r \{\mathbf{y}\}_r^T}{M_{Ar} (-I_r)} + \frac{\{\mathbf{y}\}_r^* \{\mathbf{y}\}_r^{*T}}{M_{Ar}^* (-I_r^*)} \right] \quad (4)$$

These equations reveal that an expression for flexibility is generated when the frequency response function matrix, $[H(\omega)]$, is evaluated at $\omega = 0$. Through previous research, it has been shown that this expression provides a good estimate, or measure, of in-situ structural flexibility [3,5]. It should be pointed out that the flexibility matrices established for both lanes through Equation (4) provide the same measure, or estimate, of in-situ flexibility along the Girder 3 test points (refer to the deflection profiles in Figure 7). In other words, regardless of which set of lane parameters are used, the measure of flexibility for the common region, Girder 3, is consistent.

5.1. Spliced Results

MAC was computed between the two sets of modes identified from the two lane tests. Several resulting MAC

values are presented below in Table 2.

Northbound Lane Test	Southbound Lane Test	MAC
Mode 1 - 4.957 Hz	Mode 1 - 4.953 Hz	0.998
Mode 2 - 5.468 Hz	Mode 2 - 5.442 Hz	0.994
Mode 3 - 7.265 Hz	Mode 3 - 7.239 Hz	0.978
Mode 4 - 8.172 Hz	Mode 4 - 8.137 Hz	0.922
Mode 5 - 8.704 Hz	Mode 5 - 8.624 Hz	0.987
Mode 6 - 9.075 Hz	Mode 6 - 8.931 Hz	0.991
Mode 7 - 11.840 Hz	Mode 7 - 11.936 Hz	0.996
Mode 8 - 14.183 Hz	Mode 8 - 14.178 Hz	0.991
Mode 9 - 14.699 Hz	Mode 9 - 14.714 Hz	0.987
Mode 10 - 22.422 Hz	Mode 10 - 22.319 Hz	0.975
Mode 11 - 24.215 Hz	Mode 11 - 24.143 Hz	0.925

Table 2 – Correlation Between Individual Lane Modes

The pairs of modes displaying high correlation (MAC > 0.9) were spliced together using the methods discussed in Section 2. Modal parameters from the northbound lane test served as the *Master* parameters throughout splicing whereas those from the southbound lane test served as the *Slave* parameters. Several of the comprehensive modes obtained through this particular splicing method are shown in Figure 8.

A comprehensive flexibility matrix – a matrix comprised of flexibility coefficients for spatial locations in both traffic lanes – was obtained for the test-bridge by substituting into Equation (4) the comprehensive modal parameters. Note that because the northbound lane parameters were designated as *Master* parameters throughout splicing, the eigenvalues and scaling used to compute comprehensive flexibility were those identified from northbound lane data. In other words:

$$\lambda_r = \lambda_{r \text{ comprehensive}} = \lambda_r^{\text{northbound lane}}, \text{ and;} \\ M_{Ar} = M_{Ar \text{ comprehensive}} = M_{Ar}^{\text{northbound lane}}$$

The reliability and quality of the resulting comprehensive flexibility was evaluated by comparing simulated, or comprehensive flexibility-based, truck-load displacements with displacements measured during independent truck-load tests. Simulated as well as actual measured truck-load displacements are plotted in Figure 9. Good correlation can be observed between the simulated and measured values in this figure. Such results imply that the comprehensive flexibility is structurally relevant and provides a reliable measure of existing bridge behavior/condition.

6. CONCLUSIONS

The fact that the comprehensive flexibility was deemed reliable implies that the identified modal parameters for each lane of the test-bridge were good estimates of the true parameters and that the acquired modal (impact) data was of high quality. Hence, the correlation between simulated and

measured displacements validated the applied impact methods – successful correlation revealed that objective information pertaining to in-situ bridge behavior could be successfully, and practically, acquired and evaluated when using lane-by-lane “rapid” multi-reference impact techniques in conjunction with the splicing methods discussed in this paper. The comprehensive measure of flexibility identified through these experimental and analytical modal methods can subsequently be used to predict superstructure response (displacements) to different truck types and truck-load configurations and also serve as the basis for calibration of a finite element model of the bridge. Furthermore, displacement profiles derived from this flexibility can assist visual inspections (condition evaluations) of the bridge [5] and help monitor changes in bridge condition over time [2,5].

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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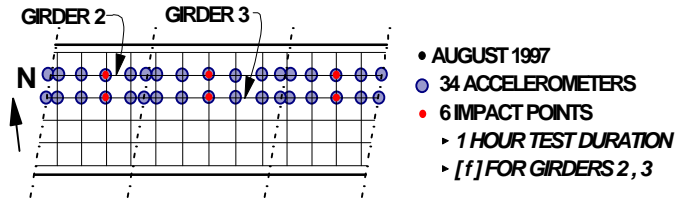


Figure 1 – Example of “rapid” multi-reference impact test layout

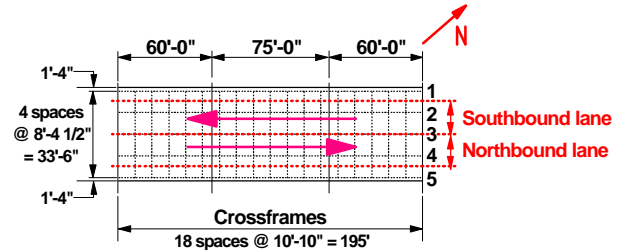


Figure 4 – Overview of test-bridge

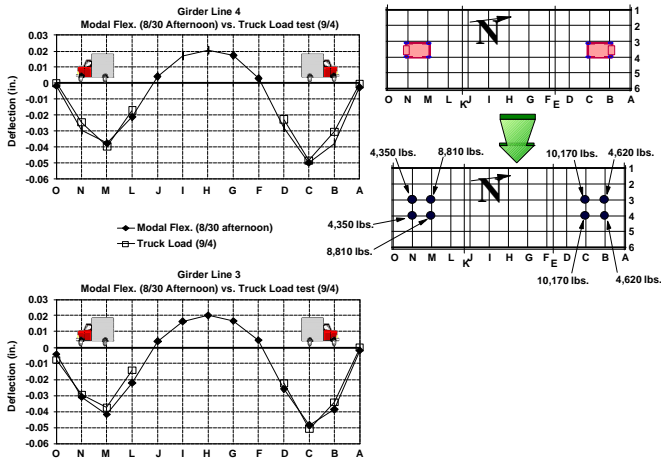


Figure 2 – Measured vs. simulated truck-load displacements

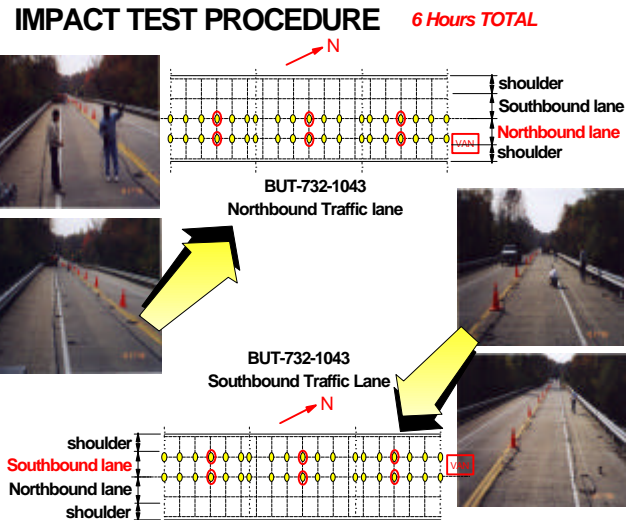


Figure 5 – “Rapid” multi-reference impact test layouts on test-bridge

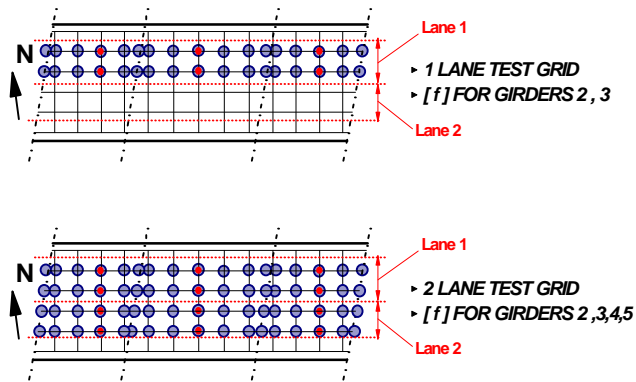


Figure 3 – One lane flexibility matrix vs. multiple lane flexibility matrix

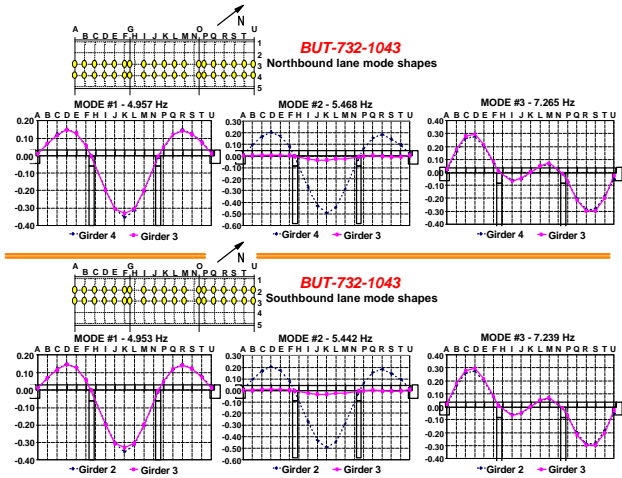


Figure 6 – First three modes identified from each lane test

FLEXIBILITY VERIFICATION BUT-732-1043 (Girder Line 3 Truck-Load Deflections)

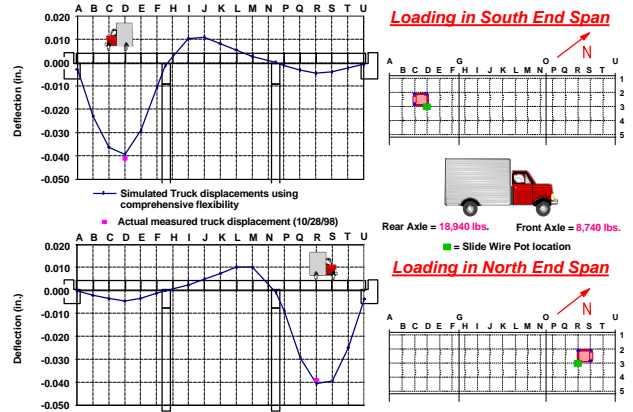


Figure 9 – Simulated (using comprehensive flexibility) vs. measured truck-load displacements

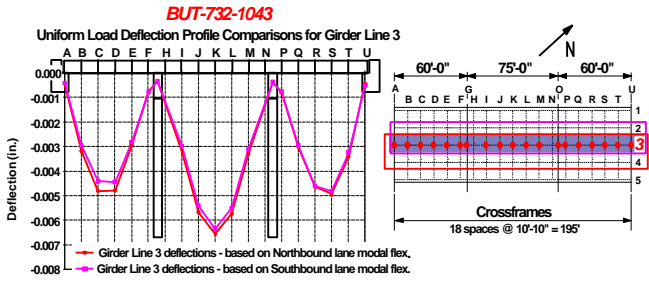


Figure 7 – Similar girder 3 deflection profiles reveal consistent measure of flexibility

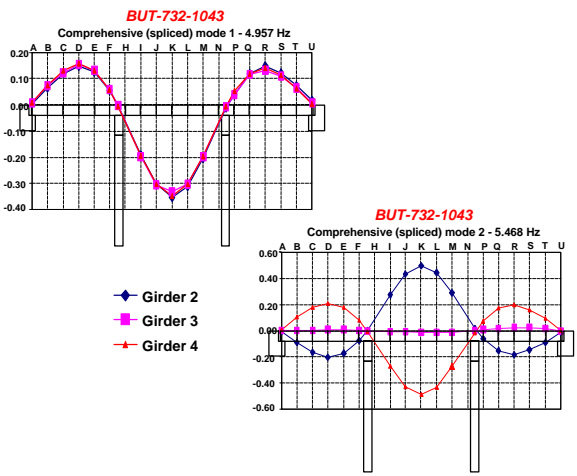


Figure 8 – Comprehensive (spliced) modes 1 and 2