

Article

Establishment of a Mounting Offset Index and Its Application to Dynamic-Response Evaluation of Long-Span Steel Structures

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Abstract

Discrete ancillary equipment and local added masses are common in long-span steel structures, yet equal total mass can produce different dynamic responses because existing quantity-based descriptions do not encode spatial redistribution. This study establishes a mounting offset index (MODI) from mass intensity M_I , eccentricity E_I , dispersion D_I , and central–subcentral synergy C_I . Shaking-table tests on a 1:40 single-layer cylindrical reticulated-shell model examined one unloaded baseline and 44 mounted-mass layouts in the X, Y, and 45° structural orientations, yielding 135 orientation-specific cases. Same-orientation normalization produced four response ratios. All the responses differed significantly among the orientations ($p < 0.001$), while the equal-mass layouts exhibited distinct MODI values and responses. In 100 repeated five-fold analyses, the four-component model achieved $Q^2 = 0.554 \pm 0.039$ for the X-orientation time-domain peak ratio and 0.364 ± 0.052 for its frequency-domain peak ratio; the composite MODI had no stable predictive capability. These results establish a hierarchical evaluation framework: the MODI supplies a pre-test spatial coordinate for layout comparison, the components support selected within-orientation interpretations, and the directional sensitivity index with the three-orientation envelope identifies direction-sensitive and relatively unfavorable measured-node responses. The MODI is therefore an engineering screening descriptor rather than a universal response-prediction formula.

Keywords: long-span steel structure; single-layer cylindrical reticulated shell; suspended mass; mounting offset index; shaking-table test



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1. Introduction

Single-layer cylindrical reticulated shells are an important form of long-span spatial structure and are widely used in industrial plants, warehouses, coal-storage facilities, and exhibition centers. Zhang and Li [1] discussed the structural design and optimization of a large-span three-centered cylindrical reticulated shell in a coal-fired power plant, demonstrating the direct industrial relevance of this structural form. San et al. [2] investigated three-dimensional aerodynamic optimization of single-layer cylindrical roofs and showed that structural geometry and loading direction jointly affect spatial response. Guo et al. [3] demonstrated, through changes in natural frequency caused by added mass, that mass increments alter structural dynamic characteristics. Nie et al. [4] evaluated the isolation performance of a four-side-supported single-layer cylindrical reticulated shell, further indicating that support conditions and response-control measures influence seismic response.

For scaled shaking-table testing, Zhang et al. [5] proposed a fabrication method for small-scale single-layer reticulated-shell models and verified it through shaking-table tests, providing a technical route for testing complex spatial structures. Nie et al. [6] analyzed the progressive collapse of a double-layer cylindrical reticulated shell with infill walls and emphasized the interaction between ancillary construction and the primary structure. Wu et al. [7] performed shaking-table tests on a single-layer aluminum-alloy cylindrical reticulated shell and provided experimental evidence of its dynamic characteristics and seismic response. Coutinho et al. [8] reviewed similitude theory and its applicability to reduced-scale models, noting that extrapolation from model tests must remain bounded by the adopted similitude relations and test conditions.

Regarding the seismic-response mechanisms of cylindrical reticulated shells, Cedron and Elghazouli [9] analyzed the seismic performance and key response features of single-layer steel cylindrical lattice shells and subsequently proposed assessment and design considerations for this structural type [10]. Liang et al. [11] experimentally verified the influence of an isolation layer on the response of a single-layer cylindrical reticulated shell. Nie et al. [12] used model tests to investigate the collapse behavior of a spatial double-layer cylindrical shell. Zhang et al. [13] developed a probabilistic dynamic-response model from small-scale shaking-table data while considering ground-motion variability. Li et al. [14] revealed the effect of coupled initial imperfections on the load-carrying capacity of a single-layer cylindrical reticulated shell. Luo et al. [15] directly investigated the influence of seismic-wave incidence direction, showing that directionality should not be neglected in the assessment of spatial structures.

From the perspective of structural configuration and response control, He et al. [16] analyzed a reticulated mega-structure containing single-layer cylindrical substructures and showed that hierarchical configurations modify seismic-response transmission. Ma et al. [17] experimentally and numerically characterized the moment–rotation relationship of semi-rigid joints and its influence on single-layer cylindrical reticulated shells. They subsequently incorporated semi-rigid joint stiffness, rise-to-span ratio, and initial imperfections into dynamic analyses and proposed a corresponding seismic-design method [18]. Xu et al. [19] studied the placement of viscoelastic dampers under stochastic seismic input, demonstrating that response-control effectiveness depends on the spatial configuration of the control components.

The research that is the most closely related to the suspended ancillary masses considered here concerns nonstructural components and suspended systems. Lu et al. [20] conducted full-scale shaking-table tests on ceilings attached to rigid and flexible long-span supporting structures and found that flexible supports amplified part of the ceiling response. Zhou et al. [21] identified damage modes in discontinuous ceilings through three-dimensional shaking-table tests and proposed construction recommendations. Jiang et al. [22] compared single- and double-layer ceilings with free boundaries and showed that boundary impact and hanger–grid connections substantially affect seismic behavior. Gong et al. [23] investigated dynamic coupling between a suspended system and its supporting structure through experiments and numerical analyses. Xu et al. [24] compared the multidimensional responses of isolated and non-isolated long-span grid structures, demonstrating the combined effects of input components and support systems on roof acceleration.

In assessment methodology, Merino et al. [25] proposed consistent floor-acceleration and displacement response spectra for the performance-based seismic design of nonstructural elements. Filiatrault and Sullivan [26] summarized the research framework and principal knowledge gaps in performance-based seismic design of nonstructural components. Wang et al. [27] reviewed seismic-force demands and factors governing floor response spectra for acceleration-sensitive nonstructural components. For experimental

modeling, Hao et al. [28] developed and validated the brass scaled model subsequently adopted in the present study.

The underlying coupling is also consistent with classical vibration-absorber theory: the response of a primary structure carrying a secondary oscillator depends on mass ratio, frequency ratio, damping, and excitation characteristics rather than added mass alone [29]. Pendulum-type suspended masses retain this tuning dependence, although geometric nonlinearity and connection flexibility can move the system away from an ideal linear absorber [30]. Recent shaking-table studies of detachable ceilings and interacting ceiling–piping systems further show that connection details and interactions between secondary systems alter acceleration transfer and damage patterns [31,32]. These findings support treating the flexible suspended units in the present experiment as coupled secondary masses while avoiding the assumption that they were intentionally tuned dampers.

Vukobratović and Fajfar [33] extended direct floor-response spectra to nonlinear non-structural components. For spatial shells, a center-hung scoreboard has been shown to modify the response of a spherical reticulated shell [34]; recent shaking-table studies have also addressed cable-stiffened cylindrical shells [35], counterweight design for scaled shell models [36], and three-dimensional isolation of spherical lattice shells [37]. These studies clarify component demands, coupling, and test-model design, but they do not provide a unified descriptor of the spatial redistribution of discrete suspended masses across a long-span shell.

Existing studies have therefore recognized the effects of structural configuration, joint stiffness, support conditions, input direction, added mass, and suspended-component coupling. Nevertheless, the combined questions of how much mass is mounted, whether it is eccentric, how widely it is dispersed, and whether a central synergy is formed are still treated using separate parameters or qualitative descriptions. In particular, layouts with the same total added mass lack a unified pre-test encoding that can be compared against multiple response measures under different structural orientations.

Accordingly, the theoretical problem addressed here is how to encode the zeroth-, first-, and second-order spatial characteristics of a discrete mounted-mass field without conflating that encoding with a response predictor. The applied problem is how to compare equal-mass layouts and direction-sensitive measured responses before detailed design checks. This study therefore proposes the mounting offset index (MODI), which transforms suspended-mass layouts at seven nodes into a calculable and rankable spatial descriptor. The MODI compares total mass, eccentricity, dispersion, and central synergy; response relationships are examined separately using the four component features.

The data comprise 45 layout states, including one unloaded baseline and 44 mounted-mass layouts, tested in the X, Y, and 45° orientations relative to uniaxial table motion. The same ground motion was used in all three test groups, and the shaking table and its direction of motion remained fixed. In the X orientation, the structural longitudinal axis was aligned with table motion; in the Y orientation, it was perpendicular to table motion; and, in the 45° orientation, the entire structure was rotated clockwise by 45° from the X orientation. After each rotation, the sensor was reinstalled at node 7 such that its X axis remained parallel to table motion and its Y axis remained perpendicular. The study develops the MODI components, extracts multiple response ratios in the direction parallel to table motion using the unloaded baseline for the same orientation, compares quantity-only, composite MODI, and four-component models, uses the directional sensitivity index (DSI) and the three-orientation envelope to describe post-test directional differences, and defines the applicability of each measure.

The objectives are to (1) formulate and physically interpret a pre-test MODI from the zeroth-, first-, and second-order moments of the mass field with a central–subcentral

correction; (2) quantify orientation effects and compare quantity-only, composite-index, and four-component descriptions using paired statistics and repeated cross-validation; and (3) establish a hierarchical framework in which the MODI describes the spatial state, the four components support selected within-orientation interpretations, and the DSI with the response envelope describes post-test directional dispersion and relatively unfavorable measured-node response.

2. Experimental Model and Methods

The study program comprised five steps. First, the scaled shell and its gravity-compensation system were installed on a fixed uniaxial shaking table. Second, one unloaded baseline and 44 suspended-mass layouts were defined. Third, the complete layout set was tested with the structure successively placed in the X, Y, and 45° orientations while table motion remained unchanged. Fourth, the node-7 acceleration records were processed into four same-orientation response ratios. Finally, the MODI, its four components, the DSI, paired statistical tests, and repeated cross-validation were used to distinguish spatial-layout description from response interpretation.

All commercial experimental equipment, including the shaking table, accelerometer, and data-acquisition hardware, was supplied by Yantai XTD Test Technology Co., Ltd. (Yantai, China). Data processing, statistical analysis, and figure generation were performed using Python 3.7 (Python Software Foundation, Wilmington, DE, USA).

2.1. Shaking Table and Model Restraint

The tests used a uniaxial shaking table driven by a linear motor. The table surface contained an array of 13 mm bolt holes spaced at 50 mm. A dedicated base was used to restrain the model reliably in the X, Y, and 45° orientations relative to the uniaxial input. The 45° orientation denotes a clockwise rotation of the structural longitudinal axis by 45° from the X orientation and does not denote triaxial input. The shaking table and base are shown in Figure 1.

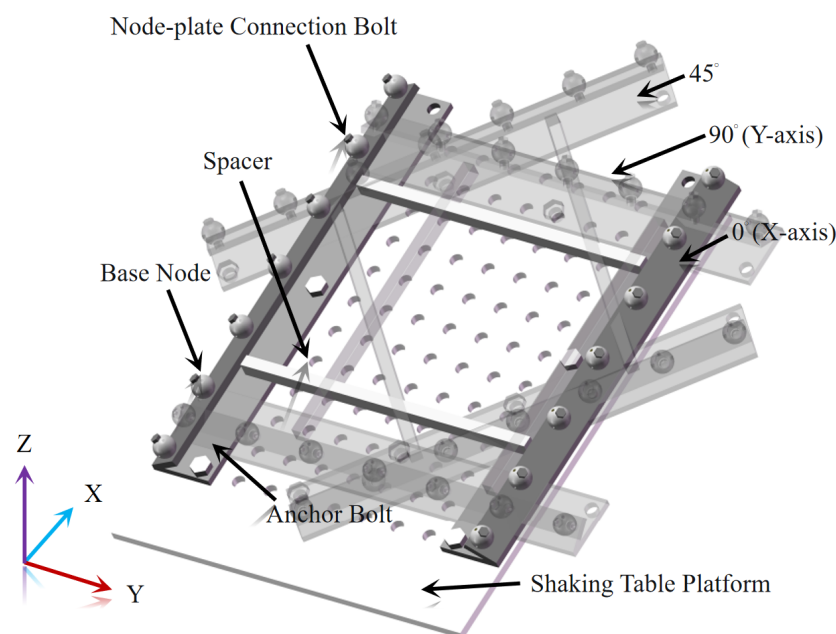


Figure 1. Shaking-table system and base used to fix the model in the three structural orientations. Modified with permission from Ref. [28].

2.2. Scaled Model

The present tests used the 1:40 H62 brass scaled model of a single-layer cylindrical reticulated shell previously developed and validated by Hao et al. [28]. The model was 600 mm long, 500 mm wide, and 250 mm high, with 30 mm diameter spherical nodes. It was fabricated using 3D-printed positioning aids and drilled-and-bonded spherical joints. Details of the similitude design, fabrication procedure, and baseline dynamic validation are reported in Ref. [28] and are not repeated here.

Gravity compensation was applied at every spherical node to preserve the designed static geometry. Each node received a 100 g counterweight and was fine-tuned with additional 30 g and 40 g disk weights so that the installed model approached its designed stress-free initial shape. The model and gravity-compensation layout are shown in Figure 2.

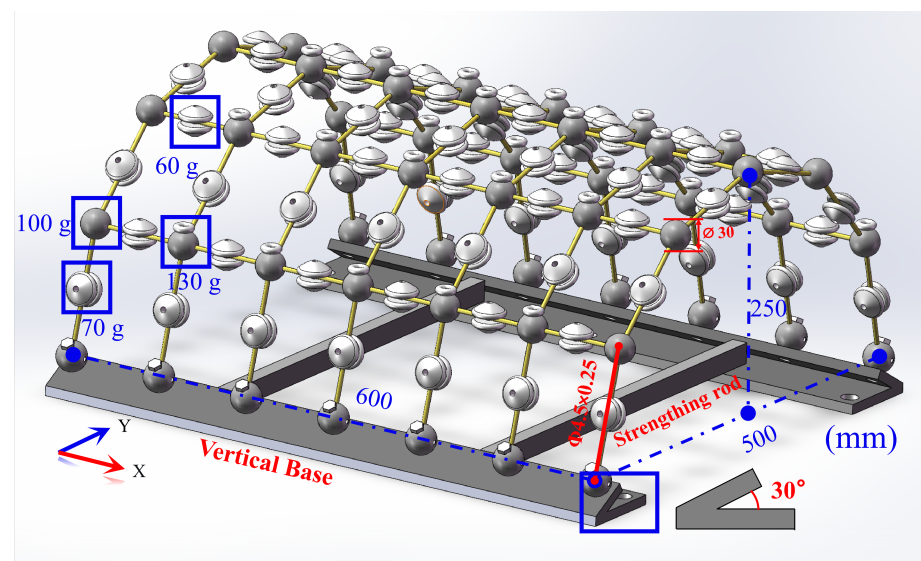


Figure 2. Scaled single-layer cylindrical reticulated-shell model and gravity-compensation arrangement. Modified with permission from Ref. [28].

2.3. Similitude Relations and Mass Compensation

This study adopts the heterogeneous-material dynamic similitude relations established by Hao et al. [28] using the Buckingham π theorem. For the elastic-stage dynamic response of the single-layer cylindrical reticulated shell, length l , stress σ , and acceleration a were selected as the basic reference quantities, and the elastic-modulus ratio was introduced to account for the material-stiffness difference between the model and prototype. Only the key similitude parameters needed to interpret the present tests are summarized here; the complete derivation and validation are available in Ref. [28].

The prototype used Q235B structural steel, whereas the model used H62 brass because its microscale machinability avoids welding heat-affected zones and cold-bending defects. The material properties are summarized in Table 1.

Table 1. Material properties of the prototype and scaled-model materials. Data adapted from Ref. [28].

Material	E (GPa)	Yield Strength (MPa)	Density (kg/m ³)	Poisson's Ratio
Q235B steel (prototype)	206	235	7850	0.30
H62 brass (model)	94	258	8900	0.34

A geometric scale of 1:40 was adopted, and the principal geometric parameters are listed in Table 2. The model was intended to compare relative responses among suspended-

mass layouts. Its results provide a reference for prototype layout evaluation but are not used to provide direct quantitative design responses for the prototype.

Table 2. Principal geometric parameters of the prototype and scaled model. Data adapted from Ref. [28].

Geometric Parameter	Q235B Prototype	H62 Brass Model
Span (m)	20	0.50
Longitudinal length (m)	24	0.60
Rise (m)	10	0.25
Member section	$\Phi 180 \times 10$ mm steel tube	$\Phi 4.5 \times 0.25$ mm brass tube
Spherical-node diameter (mm)	1200	30

The principal similitude ratios derived from the material parameters and geometric scale are summarized in Table 3. The static-displacement error and the errors in the first eight natural frequencies are taken from the model-validation results reported by Hao et al. [28] and are not presented as new validation evidence in this study.

Table 3. Principal similitude ratios and validation errors. Data adapted from Ref. [28].

Category	Quantity	Scale Ratio	Actual Ratio	Validation Error
Geometry	Length	—	1:40	—
	Area	—	1:1600	—
Material	Elastic modulus	—	1:2.19	—
	Stress	—	1.1:1	—
	Density	—	44:1	—
Loading	Concentrated force	—	1.1:1600	<3%
	Moment	—	1.1:64,000	<5%
	Surface load	—	1.1:1	<3%
Dynamics	Displacement	—	2.41:40	<3%
	Period	—	9.82:40	<5%
	Frequency	—	40:9.82	<5%
	Acceleration	—	1:1	—

The actual H62 brass/Q235B steel density ratio of approximately 1.13:1 is far below the theoretical density ratio of 44:1. Concentrated nodal mass compensation was therefore adopted. Lead-ring counterweights were fixed symmetrically above and below each spherical node, providing a total compensation mass of 5.03 kg compared with a model self-mass of 5.14 kg. Edge nodes 1 and 7 received 100 g each, and internal nodes 2–6 received 160 g each so that the overall mass distribution was consistent with the prototype similitude requirements.

2.4. Suspended-Mass Layouts and Test Matrix

The test matrix comprised 45 layout states: one unloaded baseline and 44 mounted-mass layouts. Each state was tested once in the X, Y, and 45° structural orientations relative to the uniaxial input, producing 135 orientation-specific cases. Removing the three unloaded baselines left 132 mounted cases. Each suspended unit had a mass of 0.256 kg. The approximately 45 mm dimension refers to the overall hanging length of one bent-wire hook plus one counterweight rather than the hook diameter or the hook alone. The flexible connection permitted motion during excitation, and multiple units at the same node were connected one below another in series. The maximum number of units was five, limited by installation space beneath the model rather than by structural capacity, corresponding to a maximum added mass of 1.28 kg. The previous study [28] focused on the similitude design, fabrication, and baseline dynamic validation of the model; the present study uses

the modified experimental arrangement to investigate discrete suspended-mass layouts and their orientation-dependent responses.

Layout codes specify the number of suspended units at the seven mounting nodes. For example, 0-0-1-3-1-0-0 denotes one, three, and one units at nodes 3, 4, and 5, respectively, whereas 4-5 denotes five units at node 4.

2.5. Ground-Motion Input and Measurement Point

A medium-frequency ground motion was used as the test input. The source record covered 0–9.82 s with a time step of 0.01 s, and acceleration was expressed in units of g. Its positive peak was approximately 0.193 g at 1.62 s. Figure 3 presents the time history and spectrum used to characterize the input frequency content and its relationship to the measured-response band. Frequency-domain analyses covered 0–50 Hz.

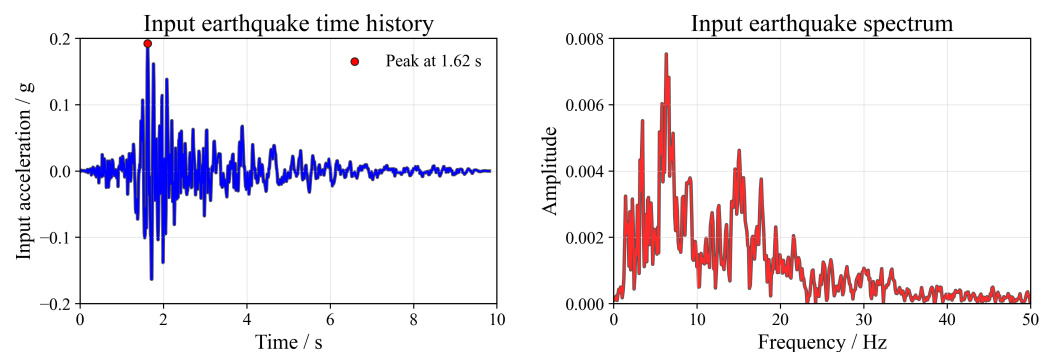


Figure 3. Original input ground-motion time history and amplitude spectrum.

2.6. Data Processing and Response Measures

The raw acceleration signals were sampled at approximately 2048 Hz. The signals were first averaged over 0.01 s intervals to obtain a common 100 Hz series. Each response channel was then transformed using the fast Fourier transform (FFT), and high-frequency components were removed using a low-pass cutoff specified separately for each case and channel rather than a common empirical frequency multiplier. Spectrum coefficients above the cutoff were set to zero, after which the time series was reconstructed by inverse FFT and mean-aligned. Finally, the time axis was shifted according to the positive peaks of the input and response, together with the existing manual time offset, and a common 0–10 s analysis window was extracted. Time shifting served only to standardize the analysis window and did not change amplitudes or frequency content; it was not used to evaluate phase differences. The original manual cutoff log was not completely retained. For internal auditability, equivalent cutoff frequencies and fitting errors were inferred from the saved raw and filtered signals. These inferred values verified the existing processed data but are not represented as the original cutoff settings.

Figure 4 compares the raw signal for case Y-4-3 with its denoised counterpart. Denoising primarily suppresses high-frequency random fluctuations while retaining the principal vibration pattern, peak interval, and decay trend.

The 30% decay time T_{30} was calculated from the final filtered time-aligned 100 Hz series over 0–10 s. The absolute peak was first defined as $A_{\max} = \max |a(t)|$. Beginning at the time of this peak, the algorithm searched for the first interval during which the signal remained no greater than $0.30A_{\max}$ for 0.20 s. At 100 Hz, this duration corresponds to 20 consecutive samples. T_{30} was defined as the difference between the beginning of that interval and the peak time. If the criterion was not met within 0–10 s, the response had not reached the prescribed decay state within the analysis window; T_{30} and R_{30} were therefore undefined for that case. Case Y-4-3 did not reach this prescribed decay state, so

the R_{30} statistics use the 43 Y-orientation cases for which the criterion was attained. In all three orientations, the sensor X channel parallel to table motion was used as the principal monitored response. The sensor Y channel perpendicular to table motion was retained as an auxiliary observation but was not used in the four principal response ratios. The two channels were not combined vectorially for the 45° orientation.

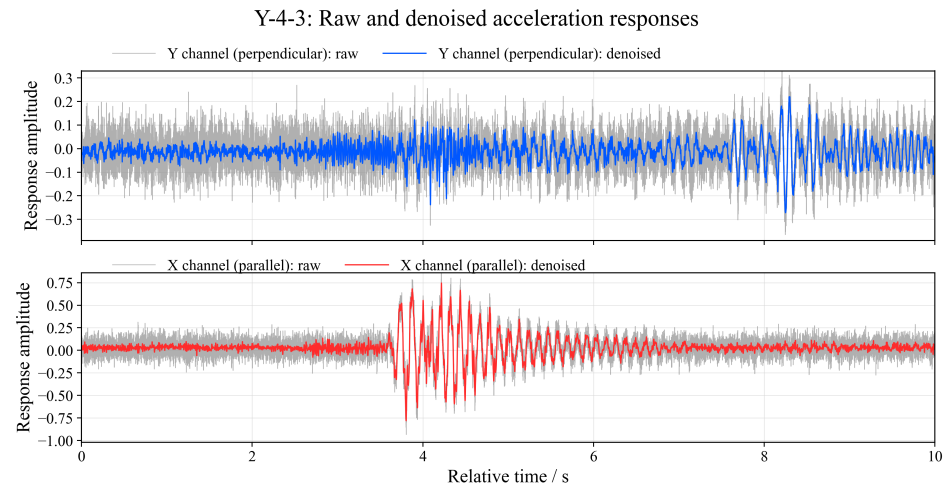


Figure 4. Raw and denoised signals for case Y-4-3.

Acceleration at node 7 was measured using an IEPE piezoelectric accelerometer with a calibrated sensitivity of $100.59 \text{ mV} / (\text{m/s}^2)$, a measurement range of $\pm 5 \text{ g}$, and a frequency range of 0.2 Hz to 5000 Hz ($\pm 1 \text{ dB}$). It was supplied by an IEPE constant-current source operating at 2 mA to 10 mA ; the sensor body weighed approximately 90 g . The sensor was magnetically attached to a $30 \text{ mm} \times 30 \text{ mm} \times 2 \text{ mm}$ steel plate bonded to the spherical node with JL-528 epoxy adhesive. To reduce the influence of instrumentation on the scaled model, only one biaxial measurement point was used. The same sensor, steel plate, node-7 position, and installation method were retained for the unloaded baseline and every mounted layout. Whenever the entire structure was reoriented, the sensor was reinstalled at node 7 with its X axis parallel and its Y axis perpendicular to table motion. Node 7 was selected for repeatable installation, observation, and clearance from the suspended units; it is not claimed to represent a modal antinode or the global maximum response. Accordingly, the measured conclusions are limited to this monitored node. The three arrangements are shown in Figure 5.

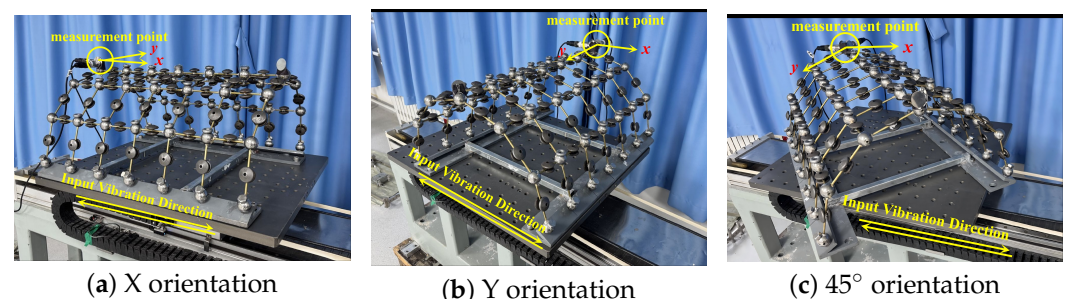


Figure 5. Photographs of the sensor installation at node 7 for the three structural orientations. The entire structure is reoriented while table motion remains fixed, and the sensor X axis is parallel to table motion in every test.

2.7. The MODI, DSI, and Statistical Analysis

The attached-mass layout was first discretized as a nodal mass sequence. Let n_i be the number of suspended units at node i and N the total number of units. Node 4 lies on the

transverse centerline; therefore, the nodal coordinate was normalized as $\xi_i = (i - 4)/3$, assigning nodes 1–7 to the interval $[-1, 1]$. This coordinate provides a common scale for comparing masses at different positions:

$$N = \sum_{i=1}^7 n_i, \quad \xi_i = \frac{i-4}{3}, \quad \xi_i \in [-1, 1]. \quad (1)$$

The MODI components describe four spatial attributes: suspended-mass quantity, unilateral eccentricity, dispersion away from the center, and synergy near the central and subcentral nodes. The mass-intensity term is

$$M_I = \frac{N}{N_{\max}}, \quad (2)$$

where $N_{\max} = 5$ for the present test matrix. This zeroth-order term measures how much mass is mounted but contains no positional information.

The eccentricity term is

$$E_I = \left| \frac{1}{N_{\max}} \sum_{i=1}^7 n_i \xi_i \right|, \quad (3)$$

where E_I is the absolute first moment of the discrete mass field and describes unilateral offset from the structural centerline. E_I is large for mass concentrated near one edge but may vanish for a symmetric layout.

The spatial-dispersion term is

$$D_I = \frac{1}{N_{\max}} \sum_{i=1}^7 n_i \xi_i^2. \quad (4)$$

As a second moment, D_I identifies mass distributed away from the center even when the layout is symmetric and E_I is approximately zero.

The central–subcentral synergy term is

$$C_I = \frac{n_4}{N_{\max}} \left[\frac{2 \min(n_3, n_5)}{N_{\max}} \right]. \quad (5)$$

It describes the combined placement of mass at the center and its two adjacent subcentral nodes. Because such a distribution is closer to the global force-transfer center than unilateral edge eccentricity, C_I is used as a stabilizing correction.

The composite index is defined as

$$\text{MODI} = 0.20M_I + 0.45E_I + 0.25D_I - 0.10C_I. \quad (6)$$

The signed weights were set empirically from the structural configuration, component scales, and intended spatial discrimination; they were not optimized against the goodness of fit of any response. They apply to the present test matrix. The MODI is used for description, ranking, and zoning, not as a universal response predictor or design limit. Robustness was examined by independently perturbing each signed weight by a uniform $\pm 20\%$ and repeating the ranking 5000 times. The Spearman correlation between perturbed and baseline rankings had a median of 0.996 and a minimum of 0.985. The top-20% layout overlap had a median of 0.889 and a minimum of 0.778. Thus, ranking was stable under moderate weight perturbation, although layouts close to zone boundaries could change position. For descriptive comparison, the zones were specified a priori as low ($\text{MODI} \leq 0.15$), medium-low ($0.15 < \text{MODI} \leq 0.30$), medium-high ($0.30 < \text{MODI} \leq 0.50$), and high ($\text{MODI} > 0.50$). These intervals organize the present data and do not represent

code-based safety classes or design thresholds. Table 4 summarizes the origin, meaning, and use of each component.

Table 4. Origin, physical meaning, and use of the MODI components.

Measure	Origin	Mathematical Form	Physical Question	Use
M_I	Total mounted quantity	$N/N_{\max}$	How much is mounted?	Basic mass intensity
E_I	First-order eccentricity	Absolute first moment	Is the mass offset to one side?	Eccentric-coupling identification
D_I	Second-order dispersion	Second moment	Is the mass far from the center?	Symmetric-dispersion identification
C_I	Central synergy	Joint central/subcentral distribution	Is a stable central synergy present?	Stabilizing correction
MODI	Composite offset	Weighted four-term combination	What is the composite spatial state?	Ranking, zoning, and screening

Unloaded baseline parameters were extracted before evaluating mounting effects to prevent intrinsic orientation-specific responses from confounding those effects. The baseline time-domain peak A_{t0} , frequency-domain peak A_{f0} , 30% decay time $T_{30,0}$, and dominant response-spectrum frequency f_{p0} were used to define

$$\alpha_d = \frac{A_{t0,d}}{\text{mean}(A_{t0})}, \quad \beta_d = \frac{A_{f0,d}}{\text{mean}(A_{f0})}, \quad \tau_d = \frac{T_{30,0,d}}{\text{mean}(T_{30,0})}, \quad \kappa_d = \left[\frac{f_{p0,d}}{\text{mean}(f_{p0})} \right]^2. \quad (7)$$

Mounted responses were normalized by the unloaded response in the same orientation. All the measures were calculated from the final 0–10 s data, specifically $A_t = \max |a(t)|$ and $R_t = A_t / A_{t0,d}$. Frequency-domain analysis excluded the 0-Hz component and was restricted to $0 < f \leq 50$ Hz. A_f was the maximum single-sided spectral amplitude, and f_p was its frequency, yielding $R_f = A_f / A_{f0,d}$ and $R_{fp} = f_p / f_{p0,d}$. The decay-time ratio was $R_{30} = T_{30} / T_{30,0,d}$.

Three models were compared: a quantity-only model containing M_I , a single-index model containing only the MODI, and a four-component model containing M_I , E_I , D_I , and C_I . The latter was

$$R_{m,d} = b_{0,d} + b_{1,d}M_I + b_{2,d}E_I + b_{3,d}D_I + b_{4,d}C_I + \varepsilon, \quad (8)$$

where m denotes the response and d the structural orientation. Identical five-fold partitions were used to compare the models. R^2 measured in-sample fit, whereas cross-validated Q^2 assessed prediction for observations excluded from model fitting:

$$Q^2 = 1 - \frac{\sum_i (y_i - \hat{y}_{i,CV})^2}{\sum_i (y_i - \bar{y})^2}. \quad (9)$$

The fixed-partition visualization presented in the Results section uses the fixed partition generated with random seed 42 for pointwise reproducibility. Model comparison in the text is based on the mean, standard deviation, and positive-value proportion from 100 repeated five-fold analyses with seeds 0–99. $Q^2 \leq 0$ indicates that cross-validated error is no smaller than that obtained by predicting the sample mean. Variance-inflation factors (VIFs) were also calculated for the four-component model. These models are used only for exploratory within-orientation interpretation and robustness assessment, not as a universal cross-orientation predictor.

No finite-element or other physics-based numerical model was constructed in this study. The models compared here are statistical regression models, and cross-validation as-

sesses only their out-of-sample behavior within the experimental dataset; it is not presented as numerical verification of the physical test model.

Because the same 44 layouts were observed in all three orientations, the data are paired. A Friedman test was first applied to each response, followed by paired Wilcoxon signed-rank tests with Holm adjustment for the three pairwise comparisons. Paired median differences, bootstrap 95% confidence intervals, and rank-biserial effect sizes were also calculated. R_{30} used the 43 layouts for which all three orientations were defined; the other responses used all 44 layouts.

Directional sensitivity for layout j was defined as

$$DSI_{t,j} = \max(R_{t,j,X}, R_{t,j,Y}, R_{t,j,45}) - \min(R_{t,j,X}, R_{t,j,Y}, R_{t,j,45}). \quad (10)$$

The three-orientation envelope was defined analogously; for example,

$$R_{t,\max}^{(j)} = \max(R_{t,j,X}, R_{t,j,Y}, R_{t,j,45}). \quad (11)$$

The DSI and the envelope were calculated only when all three directional values were defined. Because Y-4-3 did not meet the 30% decay criterion within the 0–10 s window, layout 4-3 was excluded from layout-level R_{30} analyses, leaving 43 complete layouts. The DSI is derived from measured responses and describes post-test directional range; it is not an independent pre-test predictor. Because the DSI and the envelope share the same response data, overlap between their top-20% sets is reported only as a ranking association, not as predictive accuracy. Principal-component analysis (PCA), following mean imputation and z standardization of the four response ratios, was used only for exploratory pattern identification. Table 5 summarizes the analytical purpose of each measure.

Table 5. Data measures and their analytical purposes.

Data Expression	Source	Physical Meaning	Analytical Purpose
Unloaded baseline	$A_{t0}, A_{f0}, T_{30,0}, f_{p0}$	Orientation-specific dynamics Dimensionless	Establish need for separate analyses
Response ratios	R_t, R_f, R_{30}, R_{fp}	within-orientation change	Multi-response evaluation
Orientation-specific model	$R^2, Q^2, RMSE$	Within-orientation explanation	Assess component-model capability
MODI zones	Mean, upper envelope, exceedance fraction	Layout grouping	Descriptive screening
DSI	Three-orientation maximum minus minimum	Directional sensitivity	Demonstrate that orientations are not replicates
Unfavorable envelope	Maximum over three orientations	Relative envelope response	Identify layouts for detailed review

3. Experimental Results and Relative-Response Evaluation

The results are presented in the sequence of baseline orientation differences, mounted-response statistics, orientation-specific models, MODI zones, the DSI and envelopes, equal-mass layouts, and multi-response analysis. A “relatively unfavorable” case denotes a high within-sample response rank and does not imply a code-defined safety level or failure probability. The thresholds $R > 1.2$, top-20%, and the MODI zones are analytical choices for this dataset, not design limits.

3.1. Unloaded Baseline Differences Among the Three Orientations

Table 6 lists the unloaded X-channel baseline parallel to table motion. The time-domain peaks in the X, Y, and 45° orientations were 1.699, 0.815, and 1.141, respectively; the corresponding 30% decay times were 0.67, 2.08, and 1.67 s, and the dominant frequencies were 9.8, 8.5, and 12.1 Hz. Thus, rotating the structure alone changed the baseline response at node 7 along table motion.

Table 6. Unloaded baseline responses and orientation-characteristic parameters.

Orientation	A_{t0}	A_{f0}	$T_{30,0}$	f_{p0}	α	β	τ	κ
X	1.699	0.079	0.67	9.8	1.394	0.811	0.455	0.935
Y	0.815	0.089	2.08	8.5	0.669	0.910	1.412	0.704
45°	1.141	0.125	1.67	12.1	0.937	1.279	1.133	1.426

Figure 6 further shows that the unloaded peak, persistence, and dominant spectral frequency already differed among the orientations. Consequently, their subsequent responses should not be pooled as if they belonged to a single dynamic system.

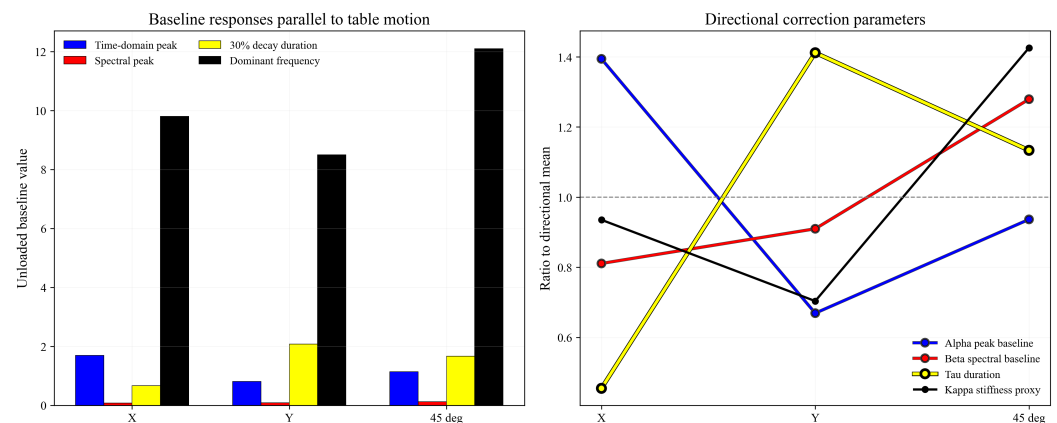


Figure 6. Unloaded baseline responses and orientation-characteristic parameters for the three structural orientations.

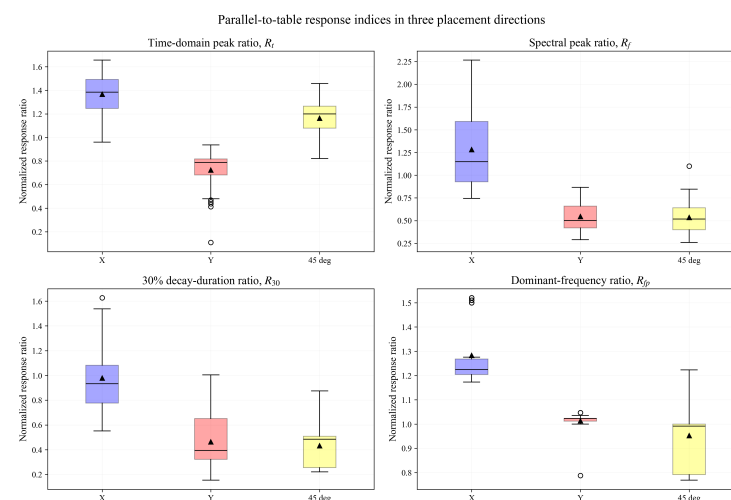
3.2. Overall Statistics for the 132 Mounted Orientation-Specific Cases

After removal of the three unloaded cases, 132 mounted orientation-specific cases remained. Table 7 summarizes the four response measures. The mean R_t and R_f were 1.367 and 1.282 in the X orientation, 0.724 and 0.545 in the Y orientation, and 1.163 and 0.535 in the 45° orientation. The Y-orientation R_{30} sample size was 43 because Y-4-3 did not meet the 30% decay criterion within the 0–10 s analysis window.

Table 7. Response-ratio statistics for the 132 mounted orientation-specific cases.

Orientation	Response	<i>n</i>	Mean	SD	Minimum	Maximum
X	R_t	44	1.367	0.163	0.960	1.656
X	R_f	44	1.282	0.428	0.744	2.266
X	R_{30}	44	0.979	0.272	0.552	1.627
X	R_{fp}	44	1.283	0.126	1.173	1.520
Y	R_t	44	0.724	0.164	0.109	0.936
Y	R_f	44	0.545	0.159	0.290	0.867
Y	R_{30}	43	0.464	0.231	0.154	1.005
Y	R_{fp}	44	1.014	0.037	0.788	1.047
45°	R_t	44	1.163	0.156	0.821	1.458
45°	R_f	44	0.535	0.183	0.259	1.100
45°	R_{30}	44	0.433	0.191	0.222	0.874
45°	R_{fp}	44	0.953	0.118	0.769	1.223

The suspended-mass effect differed clearly with structural orientation (Figure 7). The Friedman tests showed significant overall orientation effects for R_t , R_f , R_{30} , and R_{fp} ($p < 0.001$ for all). The Holm-adjusted pairwise comparisons showed significant X–Y and X–45° differences for all four responses. The Y–45° differences were not significant for R_f or R_{30} but were significant for R_t and R_{fp} . The X orientation generally produced higher R_t , R_f , and R_{fp} ; the Y orientation produced R_t , R_f , and R_{30} values predominantly below unity and R_{fp} near unity; and the 45° orientation produced R_t predominantly above unity but R_f , R_{30} , and R_{fp} mostly below unity.

**Figure 7.** Statistical distributions of the four response measures in the three structural orientations.

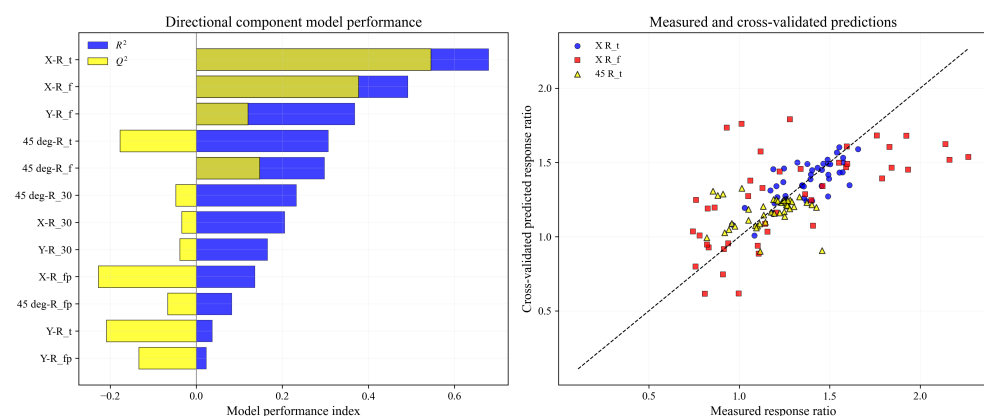
3.3. Explanatory Capability of Orientation-Specific Models

Using identical data partitions, quantity-only, composite MODI, and four-component models were compared. Across 100 repeated five-fold analyses, the four-component model yielded $Q^2 = 0.554 \pm 0.039$ for X-orientation R_t and 0.364 ± 0.052 for X-orientation R_f , with all 100 repetitions positive. Most other orientation–response combinations had low or negative mean Q^2 . The composite MODI model had negative mean Q^2 for all 12 combinations and therefore cannot be treated as a directional-response predictor. The quantity-only model showed limited positive Q^2 only for X-orientation R_f and R_{30} . The four-component VIFs ranged from 1.277 to 1.673, indicating no severe multicollinearity. A stable explanation of the X-orientation peak responses therefore arises from the joint component features, not from the fixed-weight composite MODI. The fixed-partition results are listed in Table 8.

Table 8. Fixed-partition evaluation of the four-component models.

Orientation	Response	R^2	Q^2	RMSE
X	R_t	0.680	0.545	0.091
X	R_f	0.492	0.377	0.302
X	R_{30}	0.205	−0.034	0.240
X	R_{fp}	0.136	−0.228	0.116
Y	R_t	0.037	−0.209	0.159
Y	R_f	0.368	0.120	0.125
Y	R_{30}	0.166	−0.039	0.208
Y	R_{fp}	0.023	−0.133	0.036
45°	R_t	0.307	−0.177	0.129
45°	R_f	0.298	0.147	0.151
45°	R_{30}	0.232	−0.048	0.166
45°	R_{fp}	0.082	−0.067	0.112

The fixed partition in Figure 8 shows relatively stable out-of-sample relationships for X-orientation R_t and R_f . The remaining combinations should not be described as stable predictive relationships. The fixed split permits pointwise reproduction; the conclusions regarding model differences are based on the 100 repeated five-fold analyses.

**Figure 8.** Orientation-specific model performance and cross-validated measured–predicted relationships.

3.4. MODI Zones, Upper Envelopes, and Sample Exceedance Fractions

The predefined MODI zones were used to summarize mean response, upper envelope, and the fraction of samples exceeding the analytical threshold. Large envelope responses occurred even in the low-MODI zone, confirming that the MODI describes the spatial state rather than enforcing a monotonic response–index relationship.

Figure 9 confirms that the MODI primarily organizes spatial layouts rather than guaranteeing increasing response with index value. The values in Table 9 are empirical fractions for the present sample and analytical threshold; they are neither code-defined safety limits nor population failure probabilities.

Table 9. Mean responses, upper envelopes, and sample exceedance fractions within MODI zones.

MODI Zone	n	Mean R_t	Env. R_t	$P(R_t > 1.2)$	Mean R_f	Env. R_f	$P(R_f > 1.2)$	Mean R_{30}	Env. R_{30}	$P(R_{30} > 1.2)$
Low (≤ 0.15)	24	1.122	1.571	0.625	0.930	2.266	0.250	0.666	1.537	0.130
Medium-low (0.15–0.30)	66	1.087	1.576	0.455	0.719	2.162	0.106	0.576	1.537	0.030
Medium-high (0.30–0.50)	30	1.036	1.656	0.233	0.794	1.933	0.167	0.709	1.627	0.100
High (> 0.50)	12	1.121	1.609	0.500	0.863	1.552	0.250	0.618	1.313	0.083

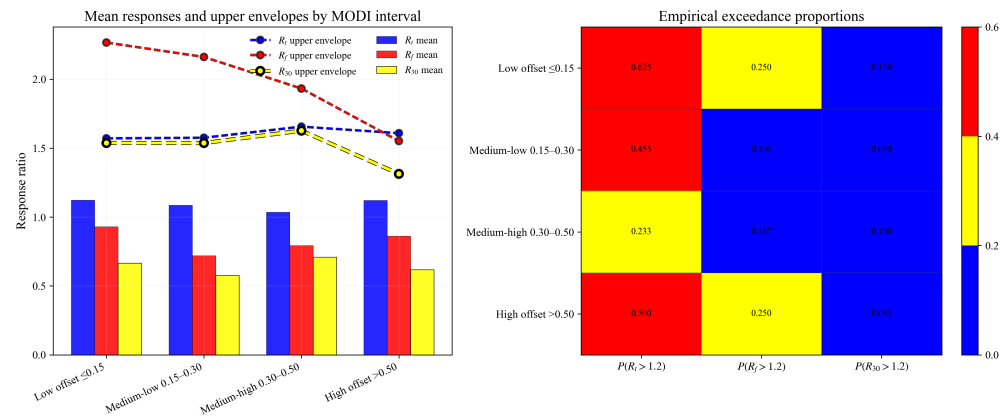


Figure 9. Response means, upper envelopes, and sample exceedance fractions across MODI zones.

3.5. DSI Directional Range and Three-Orientation Envelopes

For layouts with complete observations in all three orientations, directional sensitivity and the three-orientation envelope were calculated. Some layouts with modest MODI values exhibited large DSI values, indicating sensitivity to the orientation of excitation relative to the structure. Table 10 summarizes the top-20% ranking overlaps.

Table 10. Overlap between MODI- or DSI-ranked top-20% sets and top-20% envelope-response sets.

Response	MODI Overlap	DSI Overlap
R_t	0.444	0.222
R_f	0.222	1.000
R_{30}	0.333	0.889
R_{fp}	0.111	0.889

Figure 10 combines the response-ranking overlap with a descriptive MODI–DSI zoning framework. The horizontal and vertical boundaries are analytical partitions used to distinguish spatial offset from measured directional sensitivity; they are not code-based risk thresholds or an independent diagnostic classifier.

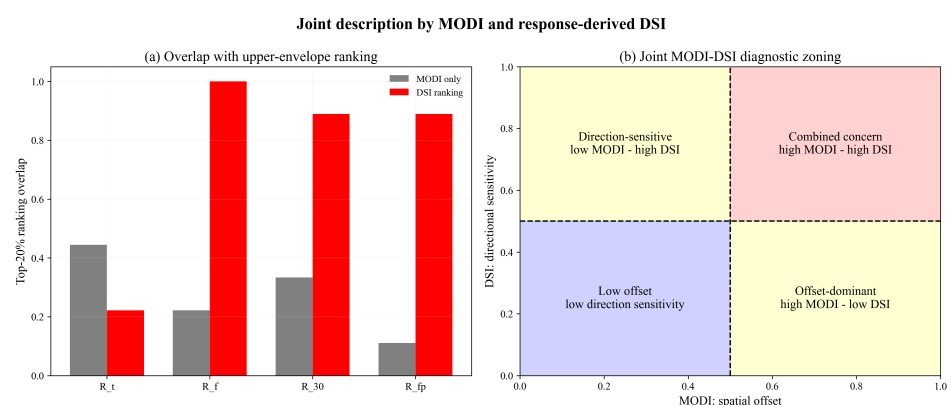


Figure 10. Joint interpretation of MODI and response-derived DSI: (a) overlap of MODI- and DSI-based top-20% rankings with the upper-envelope ranking; (b) descriptive MODI–DSI zoning used to distinguish offset-dominant, direction-sensitive, combined-concern, and low-offset layouts.

Figure 11 relates the MODI to the R_t envelope and DSI_t and summarizes the governing orientations of the three-orientation envelopes.

The DSI ranking overlapped the R_f , R_{30} , and R_{fp} envelope rankings by 1.000, 0.889, and 0.889, respectively, but overlapped the R_t ranking by only 0.222. Because the DSI and envelope response are calculated from the same three measured values, these overlaps

only describe associations between two response-derived rankings; they do not represent predictive accuracy or diagnostic efficiency on independent samples. Figure 12 further decomposes the overlap differences, governing orientations, and additional cases covered by the DSI ranking.

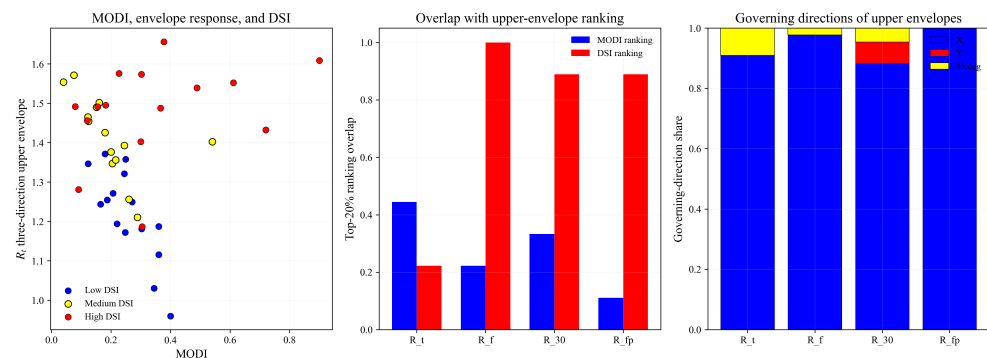


Figure 11. DSI directional ranges, top-20% ranking overlap, and controlling orientation of the three-orientation envelopes.

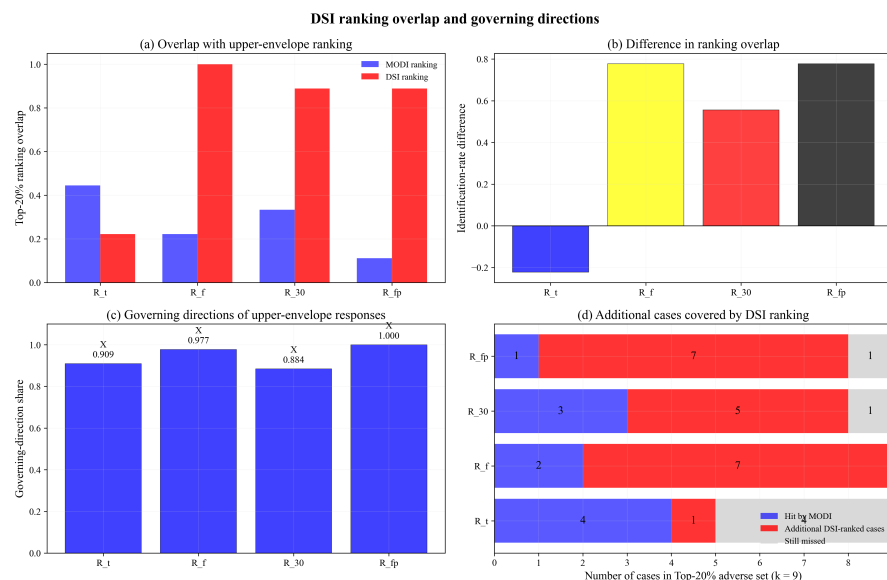


Figure 12. Expanded decomposition of DSI ranking and three-orientation envelopes: (a) top-20% ranking overlap; (b) difference between DSI- and MODI-based overlap rates; (c) governing orientations of upper-envelope responses; (d) additional envelope-ranked cases covered by DSI ranking.

3.6. Mounted Quantity, Equal-Mass Comparison, and the Need for the MODI

Figure 13 addresses why the mounted quantity N is insufficient. Although N affects dynamic response, the response means do not vary monotonically with N . Total mass is therefore a basic factor, but spatial position also matters. To remove differences in total mass, five representative layouts with $N = 5$ were compared in Table 11.

Table 11. MODI components and mean responses for representative equal-mass layouts with $N = 5$.

Layout	N	M_I	E_I	D_I	C_I	MODI	Mean R_t	Mean R_f	Mean R_{30}	Mean R_{fp}
0-0-1-3-1-0-0	5	1.000	0.000	0.044	0.240	0.187	1.098	0.630	0.436	1.096
4-5	5	1.000	0.000	0.000	0.000	0.200	1.156	0.709	0.620	1.075
1-1-0-1-0-1-1	5	1.000	0.000	0.578	0.000	0.344	0.876	0.476	0.599	1.108
2-0-0-1-0-0-2	5	1.000	0.000	0.800	0.000	0.400	0.856	0.529	0.801	1.066
1-5	5	1.000	1.000	1.000	0.000	0.900	1.284	0.712	0.473	1.102

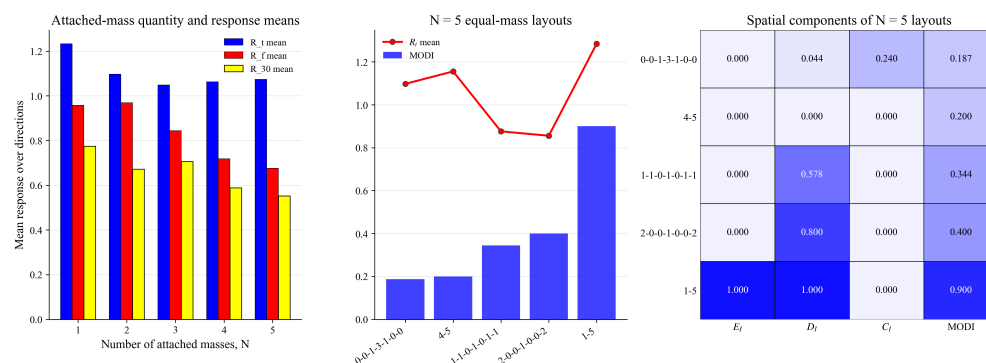


Figure 13. Mounted-quantity levels shown as grouped bars, representative equal-mass layouts with $N = 5$, and the component-value matrix for the equal-mass layouts. Blue intensity and cell annotations indicate the values of E_I , D_I , C_I , and the MODI.

Among the $N = 5$ layouts, the central-subcentral layout 0-0-1-3-1-0-0 had $\text{MODI} \approx 0.187$, the centrally concentrated layout 4-5 had $\text{MODI} \approx 0.200$, the symmetrically dispersed layout 1-1-0-1-0-1-1 had $\text{MODI} \approx 0.344$, the symmetric edge-dispersed layout 2-0-0-1-0-0-2 had $\text{MODI} \approx 0.400$, and the unilateral edge layout 1-5 reached $\text{MODI} = 0.900$. Although the total number of units was identical, the eccentricity, dispersion, central synergy, and response characteristics differed. Thus, N answers only how much mass is mounted, whereas the MODI also encodes where it is mounted, whether it is eccentric or dispersed, and whether central synergy is present. Figure 14 presents the five layouts, component indices, and response ranges together to make these equal-mass spatial differences explicit.

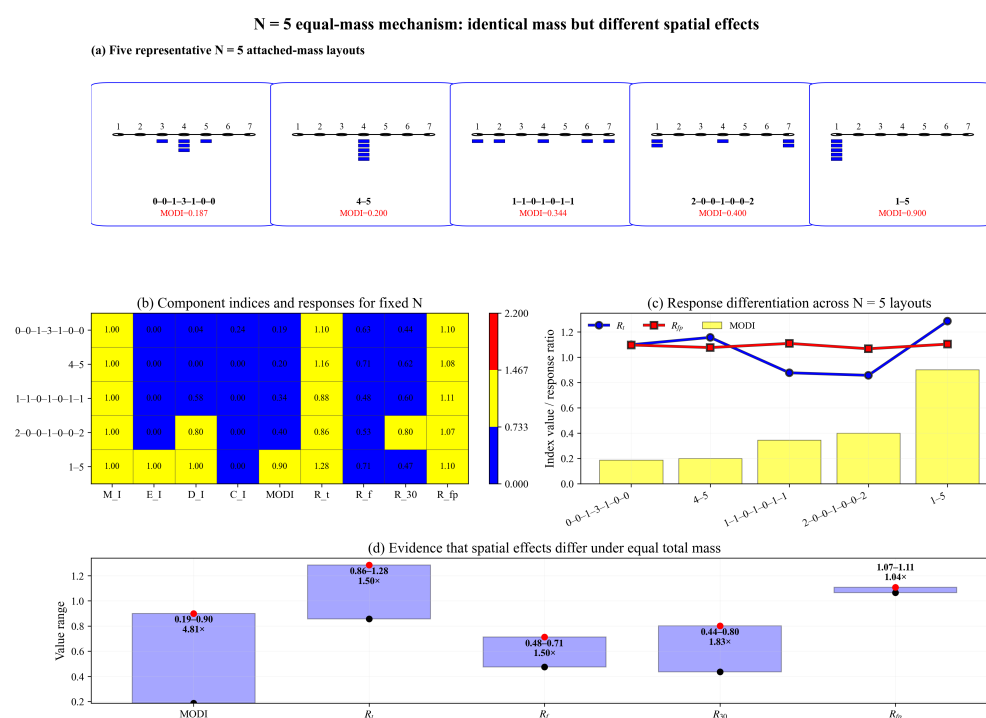


Figure 14. Mechanism comparison for five representative equal-mass layouts with $N = 5$: (a) spatial mounting patterns; (b) MODI components and mean responses; (c) response differentiation across layouts; (d) ranges demonstrating that identical total mass does not imply identical spatial indices or dynamic responses.

3.7. Standardized Coefficients, Multi-Response Profiles, and Model Boundaries

Figure 15 combines standardized regression coefficients for the MODI components, relatively unfavorable response profiles, the response-correlation matrix, and PCA response patterns. The coefficient heat map shows that the directions and magnitudes of the linear associations of M_I , E_I , D_I , and C_I vary across orientations and responses; these coefficients are not interpreted causally. PCA was used only to explore response patterns and does not directly validate the generality of the MODI. Table 12 lists the three relatively unfavorable cases for each response measure.

Table 12. Three relatively unfavorable cases for each response measure.

Response	Orientation	Layout	N	MODI	Response Ratio	M_I	E_I	D_I	C_I
R_t	X	3-5	5	0.378	1.656	1.000	0.333	0.111	0.000
R_t	X	1-5	5	0.900	1.609	1.000	1.000	1.000	0.000
R_t	X	3-3	3	0.227	1.576	0.600	0.200	0.067	0.000
R_f	X	0-0-1-0-1-0-0	2	0.091	2.266	0.400	0.000	0.044	0.000
R_f	X	3-3	3	0.227	2.162	0.600	0.200	0.067	0.000
R_f	X	3-1	1	0.076	2.139	0.200	0.067	0.022	0.000
R_{30}	X	1-2	2	0.360	1.627	0.400	0.400	0.400	0.000
R_{30}	X	1-1	1	0.180	1.537	0.200	0.200	0.200	0.000
R_{30}	X	3-1	1	0.076	1.537	0.200	0.067	0.022	0.000
R_{fp}	X	0-0-1-1-1-0-0	3	0.123	1.520	0.600	0.000	0.044	0.080
R_{fp}	X	1-1-0-1-0-1-1	5	0.344	1.520	1.000	0.000	0.578	0.000
R_{fp}	X	4-1	1	0.040	1.520	0.200	0.000	0.000	0.000

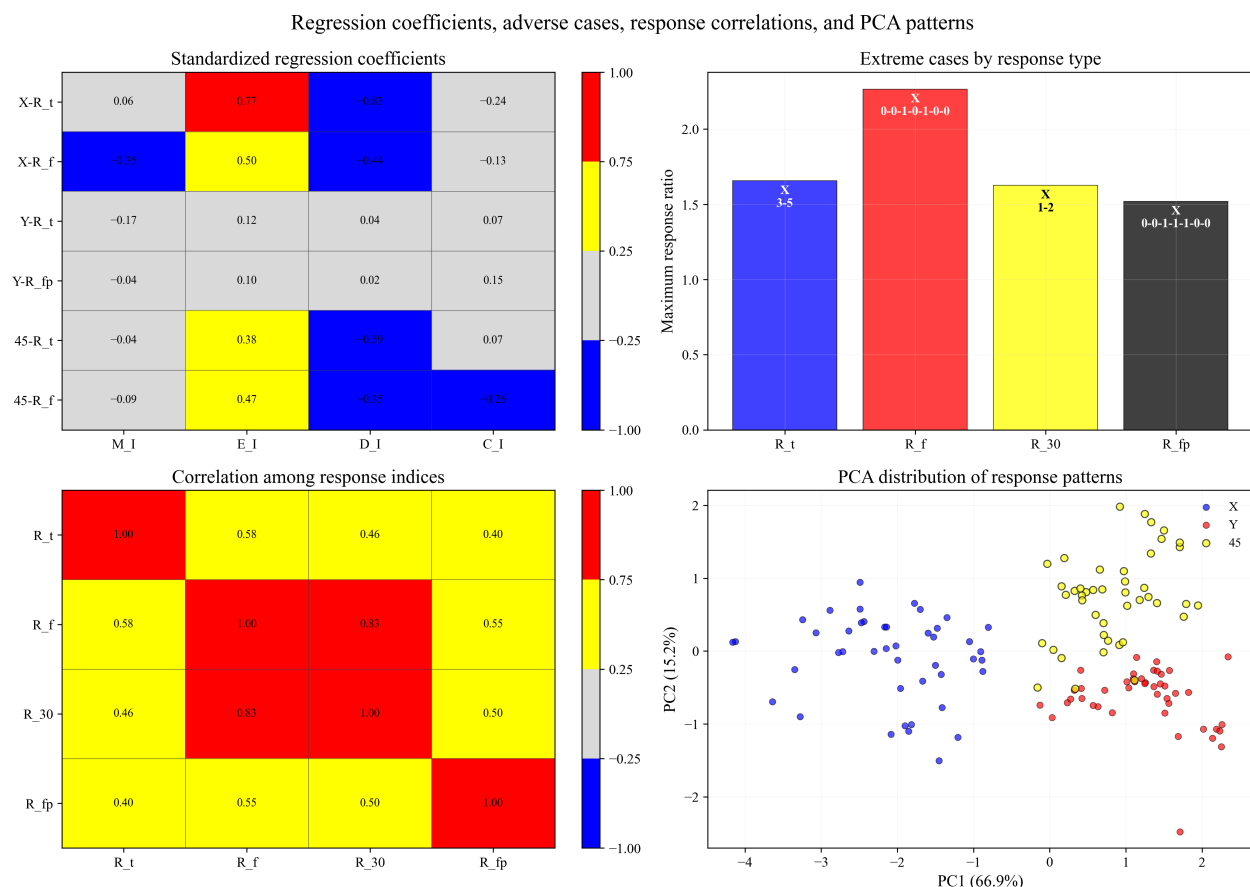


Figure 15. Standardized MODI-component coefficients, relatively unfavorable response profiles, response correlations, and PCA patterns.

The largest three-orientation envelope for each response was controlled primarily by the X orientation, but the controlling layouts differed among R_t , R_f , R_{30} , and R_{fp} . The correlation matrix and PCA indicate stronger associations among some responses, but no

single response can replace all four. A multi-response evaluation is therefore necessary, and the MODI cannot replace detailed finite-element analysis or member-force verification.

Figure 16 compares the measured response ratios, the MODI, and the four components for the relatively unfavorable cases. Most high-response points were not concentrated in the high-MODI zone. Additional checks of the top-3, top-5, and top-9 cases gave the same tendency, further confirming that the composite MODI cannot replace response calculations or measurements.

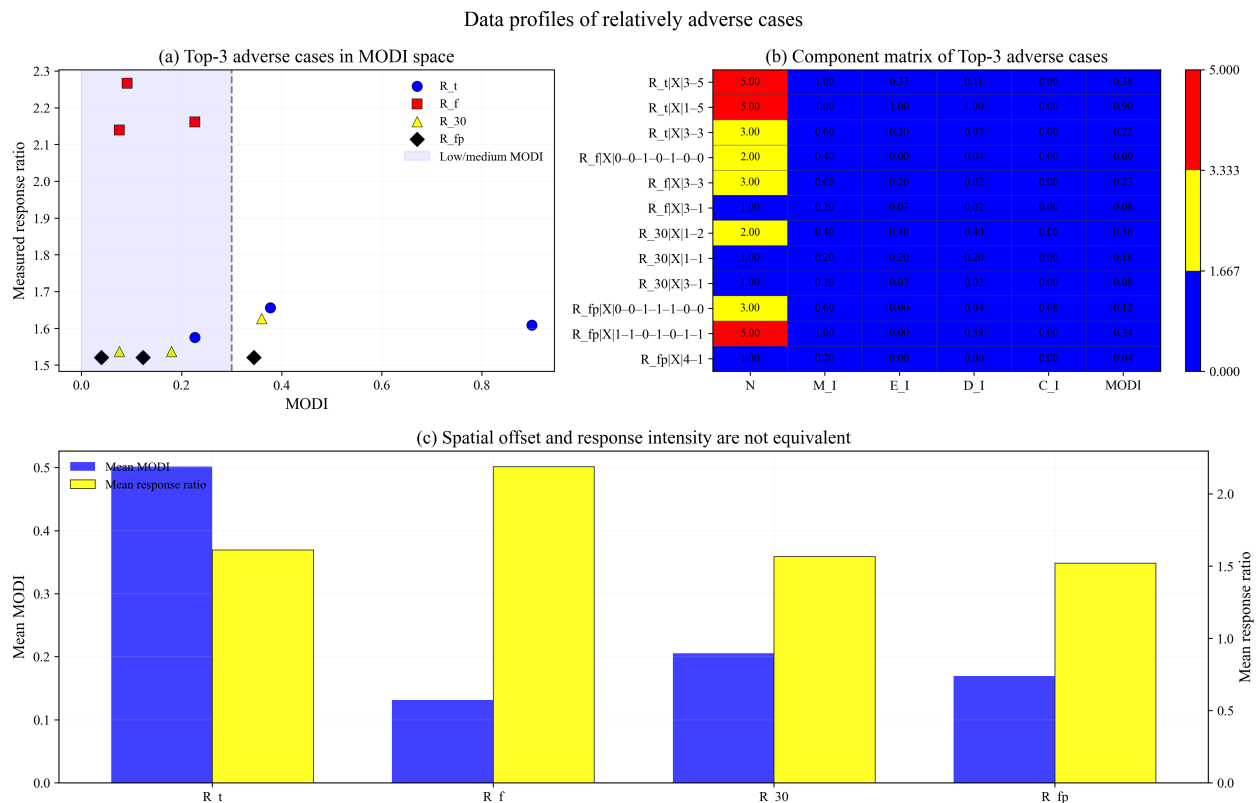


Figure 16. Data profiles of relatively unfavorable cases: response ratios, MODI components, and spatial layouts.

4. Discussion

4.1. Orientation-Dependent Response and Suspended-Mass Coupling

Across the 132 mounted orientation-specific cases, the mean R_t and R_f in the X orientation were 1.367 and 1.282, corresponding to increases of 36.7% and 28.2% relative to the unloaded baseline in the same orientation. In the Y orientation, the mean R_t and R_f were 0.724 and 0.545, with maxima of 0.936 and 0.867, indicating general suppression of response parallel to table motion. In the 45° orientation, the mean R_t was 1.163 with a maximum of 1.458, whereas the mean R_f was only 0.535. The mean R_{30} values were 0.979, 0.464, and 0.433, and the mean R_{fp} values were 1.283, 1.014, and 0.953 in the X, Y, and 45° orientations, respectively. The Friedman tests returned $p < 0.001$ for all four responses. The pairwise comparisons showed the most consistent differences between X and each of the other orientations, whereas Y and 45° did not differ significantly in R_f or R_{30} . After the response channel was consistently defined as parallel to table motion, the directional pattern was generally of high response in X, low response in Y, and a response-dependent intermediate state in 45°.

This strong directional contrast is consistent with prior observations that seismic incidence direction changes the response of cylindrical shells [15] and that secondary suspended systems interact dynamically with flexible supporting structures [20,23,31]. The

present data add an equal-layout comparison: table motion and the input record were unchanged, while rotating the shell changed the unloaded node-7 peak from 1.699 in X to 0.815 in Y and 1.141 at 45°. Consequently, the mounted response cannot be attributed to added mass alone. Anisotropic shell stiffness, orientation-dependent modal participation, and pendular motion of the suspended units are plausible contributors, but the single-point measurements and absence of identified suspension frequencies do not permit their separate quantification.

4.2. Interpretation and Engineering Scope of the MODI

Model comparison separated the roles of the composite index and its component features. Across 100 repeated five-fold analyses, the four-component model achieved $Q^2 = 0.554 \pm 0.039$ for X-orientation R_t and 0.364 ± 0.052 for X-orientation R_f , with all the repetitions being positive. The corresponding value for 45°-orientation R_f was only 0.063 ± 0.098 , with 81% positive values, and several other combinations had negative means. The mean Q^2 for the composite MODI model was negative for all 12 orientation–response combinations. The Pearson correlations between the MODI and the three-orientation envelopes of R_t , R_f , R_{30} , and R_{fp} were 0.048, -0.077 , -0.082 , and 0.164, respectively. A fixed-weight MODI can therefore describe the spatial state, but aggregation loses information because the associations of its components vary across responses. The out-of-sample explanatory capability for X-orientation peak response belongs to the four-component feature set, not to the composite index.

The MODI-zone results were not monotonic. In the low zone, the mean, envelope, and threshold-exceedance fraction for R_t were 1.122, 1.571, and 0.625, compared with 1.121, 1.609, and 0.500 in the high zone. The low-zone R_f envelope of 2.266 also exceeded the high-zone envelope of 1.552. Among the five representative $N = 5$ layouts, the MODI increased from 0.187 to 0.900, a factor of approximately 4.81, while the mean R_t ranged from 0.856 to 1.284 and the mean R_{fp} ranged only from 1.066 to 1.108. These equal-quantity differences confirm that N cannot describe eccentricity, dispersion, or central synergy. The nonmonotonic relation further confirms that a spatial descriptor cannot replace dynamic-response evaluation.

The four components have distinct physical roles. M_I represents the total secondary mass available for coupling; E_I represents a unilateral first moment that can distinguish left–right offset; D_I represents a second moment that remains nonzero for symmetric edge distributions; and C_I distinguishes center–subcenter combinations that the first two moments alone cannot separate. Their coefficients vary among directions and response measures, which explains why combining them into one fixed-weight MODI reduces response information. The sensitivity analysis nevertheless showed stable spatial ranking under $\pm 20\%$ independent weight perturbations (median Spearman correlation 0.996; minimum 0.985), supporting the use of the MODI as a layout coordinate rather than a calibrated response equation.

The ranking association between the DSI and envelope response was response-dependent. The overlap between the MODI-ranked and envelope-response top-20% sets was 0.444, 0.222, 0.333, and 0.111 for R_t , R_f , R_{30} , and R_{fp} , whereas the corresponding DSI overlaps were 0.222, 1.000, 0.889, and 0.889. The maximum envelope of every response was controlled by the X orientation: $R_t = 1.656$ occurred at MODI = 0.378, $R_f = 2.266$ at MODI = 0.091, $R_{30} = 1.627$ at MODI = 0.360, and one controlling case with $R_{fp} = 1.520$ had MODI = 0.123. Because the DSI and the envelope share the same measured directional responses, high overlap has a mathematical coupling basis and must not be interpreted as predictive or diagnostic accuracy.

For engineering use, the proposed hierarchy is transferable in concept to other spatial structures carrying discrete ancillary masses: Node coordinates and $N_{\max}$ can be redefined for the target topology, the MODI can rank candidate layouts before testing or detailed analysis, and direction-specific baselines and response envelopes can then identify cases requiring closer examination. The numerical weights and zone boundaries are not directly transferable, however. They must be recalibrated and independently validated for other shell forms, support conditions, mass ratios, connection types, and excitation sets. This restricted use is consistent with contemporary nonstructural-component assessment, in which support flexibility and nonlinear secondary-system behavior require system-specific response evaluation [31,33].

4.3. Uncertainty and Limitations

The experiment used one scaled single-layer cylindrical reticulated shell, one medium-frequency ground motion, 45 layout states, and three relative orientations, giving 135 orientation-specific cases, of which 132 contained mounted masses. Each mounted case and corresponding unloaded baseline was tested once, and one biaxial sensor was placed at node 7. The approximately 90 g sensor body was kept identical across all the tests, but its mass and the mounting plate may still influence this small-scale model. Because each response ratio shares a single baseline denominator for its orientation, denominator uncertainty and repeat-test dispersion cannot be quantified. The approximately 45 mm overall hook-counterweight unit and serial connections permitted pendular motion; their natural frequencies, damping, slip, and connection nonlinearity were not identified separately. These effects belong to the tested configuration but prevent idealization as a tuned linear secondary oscillator. The results therefore support relative ranking, orientation comparison, and screening only for the monitored node and present test matrix; they do not quantify whole-structure response or extrapolation error across structures and ground motions. Future validation should use multiple records with different spectral characteristics, repeated tests, additional measurement points, and independent structural systems, together with member-force, strain, connection-slip, and damage observations.

5. Conclusions

Based on uniaxial shaking-table tests of a scaled single-layer cylindrical reticulated shell, this study proposed the MODI and combined it with the DSI and three-orientation response envelopes to evaluate the influence of suspended-mass layouts on acceleration at node 7. The conclusions are grouped by their theoretical, engineering, and validation implications.

5.1. Theoretical Findings

1. The MODI converts a discrete mounted-mass field into a spatial coordinate containing mass intensity, first-moment eccentricity, second-moment dispersion, and central-subcentral synergy. The nonmonotonic response relations demonstrate that this coordinate describes layout state but cannot replace dynamic-response analysis.
2. Structural orientation relative to fixed table motion is a controlling variable. For the response parallel to table motion, X generally produced higher peak and frequency-domain responses, Y generally produced lower responses, and 45° produced a response-dependent intermediate state. Peak amplitude, spectral amplitude, decay persistence, and dominant frequency did not change synchronously.
3. The four-component feature set showed stable cross-validated explanatory capability only for selected X-orientation peak responses, whereas the fixed-weight composite

MODI did not show stable predictive capability. The DSI is a post-test directional-range measure, not an independent predictor.

5.2. Engineering Implications

For preliminary layout evaluation, total mounted quantity should be supplemented by eccentricity, dispersion, and center–subcenter placement. Candidate layouts can first be ranked using the MODI, then checked using orientation-specific unloaded baselines, multiple response measures, the DSI, and the three-orientation envelope. The resulting ranking is a relative screening aid and does not define a code safety class, failure probability, or universal design threshold.

5.3. Validation Needs

The conclusions are limited to the monitored node, one model, one ground-motion record, and one test per layout. The MODI weights and response relationships require validation using multiple records, repeated tests, additional measurement points, and other structural and suspension systems, with internal-force, deformation, and damage measures added where possible.

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Conflicts of Interest: Chao Sun is currently employed by Yantai XTD Test Technology Co., Ltd. Hanwei Wang and Yanan Sun are currently employed by China Construction Third Engineering Bureau Group Co., Ltd. Neither company provided financial support for this study or influenced the research design, data collection, data analysis, interpretation of the results, preparation of the manuscript, or decision to publish. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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