On the Dynamic Analysis of a Beam Carrying Multiple Mass-Spring-Mass-Damper System

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The exact natural frequencies, mode shapes, and the corresponding orthogonality relations are important in forced vibration analysis via modal expansion. In the present paper, a free vibration analysis is conducted to determine the exact natural frequencies and mode shapes of an axially loaded beam carrying several absorbers. An explicit expression is presented for the generalized orthogonality relations. These generalized orthogonality conditions are employed along with the assumed modes method to perform forced vibration analysis. The present approach is compared to other approximate methods in the literature with the classical orthogonality relations and different choice of mode shapes. The results indicate that the use of the generalized orthogonality relation with the exact mode shapes is required for a precise investigation of the dynamic response of a beam with mass-spring-mass-damper system.

1. Introduction

The study of beam vibrations is attracting continued interest all these years because of the wide range of engineering applications involving beams. Beam models are used to idealize buildings components, bridges, overhead transmission lines, microelectromechanical systems, and many more. In the case of overhead transmission lines a single conductor may be modeled as a beam that is subjected to a tensile load with the damper represented as a mass-spring-damper-mass system.

Numerous authors have studied the free and/or forced response of beams carrying in-span mass or spring-mass systems. In most investigations on the free vibration, different authors have used analytical methods to determine the exact solutions for the natural frequencies and mode shapes (e.g., [1–13] and references mentioned therein).

There are, however, few published exact solutions of the forced vibration problems. The most common analytical approach used in forced vibration analysis is based on the assumed modes method in conjunction with the classical orthogonality conditions which may be expressed as

\[ \int_0^L Y_i Y_j dx = \delta_{ij}, \]

where \( L \) is the length of the beam, \( Y_i \) and \( Y_j \) are the \( i \)th and \( j \)th normal mode shapes, respectively, and \( \delta_{ij} \) is the Kronecker delta function. Hereinafter a beam without mass or spring-mass system is referred to as a bare beam, or else it is called a loaded beam.

In [14–16], the authors employed the mode shapes of the bare beam and the classical orthogonality condition to study the forced response of loaded beams. Combinations of the mode shapes of the loaded beam with the classical orthogonality relation were employed in [17–23]. These two approaches are simple and easy to implement and, in some cases, give very good approximations. However, it was shown in [21, 24] that the mode shapes of the loaded beam and those of the bare beam are different. Further, Hassanpour et al. [25] showed that the mode shapes of the loaded beam were not orthonormal under the classical orthogonality conditions. They also presented the generalized orthogonality conditions for an axially loaded beam with in-span concentrated mass and springs. The study ignored the case where a suspended mass is connected to the beam via a spring-dashpot system.

The majority of the studies reported in the literature focused on the study of beams with either an in-span mass or spring-mass system. A series combination of each type
2. Equations of Motion

A schematic of a beam with several in-span mass-spring-damper-mass systems is depicted in Figure I. The system kinetic energy $\mathcal{T}$ and potential energy $\mathcal{V}$ may be expressed as

$$\mathcal{T} = \frac{1}{2} m \int_{L_{i-1}}^{L_i} \dot{w}^2_i(x,t) \, dx + \frac{1}{2} M_{di} \dot{\zeta}_i^2 + \frac{1}{2} M_i \dot{\zeta}_0^2,$$

$$\mathcal{V} = \sum_{i=1}^{N} \left( \frac{1}{2} EI \int_{L_{i-1}}^{L_i} w''_i(x,t) \, dx + \frac{1}{2} c_{di} (\dot{\zeta}_i - \dot{\zeta}_0)^2 + \frac{1}{2} c_i (\dot{\zeta}_0 - \dot{\zeta}_i)^2 \right) + \frac{1}{2} k_i (\zeta_0 - \zeta_i)^2 + \frac{1}{2} T \int_{L_{i-1}}^{L_i} w''_i(x,t) \, dx,$$

where $\zeta_0(t) = w_i(L_i, t)$, $EI$ is the beam flexural rigidity, $m$ is the mass per unit length of the beam, and $T$ is the beam pretension. The overdots and primes denote temporal and spatial derivatives, respectively. The subscript "i" denotes the position of the mass-spring-damper-mass system and "N" is the total number of attached mass-spring-damper-mass systems. The beam is assumed to be uniform and the pretension is constant.

Introducing these energies equations into Hamilton’s principle and adding the forcing term $F(x,t)$ yield the equations of motion and continuity conditions:

$$E I w'''_i + m \ddot{w}_i - T w''_i = F(x,t),$$

$$M_{di} \ddot{\zeta}_i + k_i (\zeta_i - \zeta_0) + c_{di} (\dot{\zeta}_i - \dot{\zeta}_0) = 0,$$

$$w_i(L_i, t) = w_{i+1}(L_i, t),$$

$$w_i(L_i, t) = w_{i+1}(L_i, t),$$

$$w''_i(L_i, t) = w''_{i+1}(L_i, t) - M_i \ddot{\zeta}_0 + EI w'''_i(L_i, t) - T w''_i(L_i, t) - k_i (\zeta_0 - \zeta_i) - c_{di} (\dot{\zeta}_0 - \dot{\zeta}_i),$$

$$-E I w'''_{i+1}(L_i, t) + T w''_{i+1}(L_i, t) = 0.$$

The deformations $w_i(x_i, t)$ and displacements $z(t)$ are expressed as

$$w_i(x_i, t) = L W_i(\zeta) e^{i \omega t},$$

$$z_i(t) = L A_i e^{i \omega t},$$

where $W_i(\zeta)$ and $A_i$ are the respective nondimensional amplitudes of $w_i(x_i, t)$ and $z_i(t)$ and $\omega$ is the circular complex natural frequency of the system. Substituting (8) into (2)–(7) yields the following nondimensional system equations:

$$W'''_i(\xi) - s^2 W''_i(\xi) + \Omega^2 W_i(\xi) = 0,$$

$$A_i - K_i W_i(\xi) = 0,$$

where

$$W_i(\xi) = c_i \sin \alpha \zeta_i + c_2 \cos \alpha \zeta_i + c_3 \sinh \beta \zeta_i + c_4 \cosh \beta \zeta_i.$$

Substituting (8) into (3)–(7) yields

$$W_i(\xi) = W_{i+1}(\xi),$$

$$W_i'(\xi) = W_{i+1}'(\xi),$$

$$W_i''(\xi) = W_{i+1}''(\xi),$$

$$W_i'''(\xi) - \eta_i W_i(\xi) + \gamma_i A_i = 0,$$

where the following nondimensional variables are used:

$$\xi_i = \frac{L_i}{L}, \quad A_i = K W_i(\xi),$$

$$K_i = \frac{k_i + \omega c_{di}}{k_i + M_{di} \omega^2 + \omega c_{di}}, \quad s^2 = \frac{T L^2}{EI},$$

$$\Omega^2 = \frac{m \omega^2 L^4}{EI}, \quad \eta_i = \frac{k_i + \omega^2 M_i + \omega c_{di} L^3}{EI},$$

$$\gamma_i = \frac{k_i + \omega c_{di} L^3}{EI}, \quad \zeta = \frac{x}{L},$$

$$\alpha = \sqrt{s^2 + \frac{s^4}{4} + \Omega^4}, \quad \beta = \sqrt{s^2 + \frac{s^4}{4} + \Omega^4}.$$

Substituting (10) into (15) yields

$$W_i'''(\xi) - W_{i+1}'''(\xi) + W_i(\xi) (K_i Y_i - \eta_i) = 0.$$

The use of any classical boundary conditions at each end of the beam along with (12)–(14) and (17) yields a set of 4 + 4N algebraic homogeneous equations (4 equations from the boundary condition at the ends and 4N equations from the continuity relations). These algebraic equations are linear in the unknown coefficients (C’s) and they can be presented in matrix format as

$$[\mathcal{F}]_{(4+4N)X(4+4N)} [C]_{(4+4N)X(1)} = [0]_{(4+4N)X1}.$$
where the elements of the matrix \( \mathcal{F} \) are listed in the Appendix. A nontrivial solution is obtained when matrix \( \mathcal{F} \) is singular. Hence, the characteristic or frequency equation is obtained as

\[
\det([\mathcal{F}]_{(4+N)(4+N)}) = 0. \tag{19}
\]

The mode shapes associated with each beam segment are obtained by substituting the integration constants from (18) into (11). An example of a matrix that yields the frequency equation is provided in the Appendix for the case of a cantilever beam with one in-span mass-spring-damper-mass support.

### 4. Generalized Orthogonality Relations

The solution of the equations of motion, (2) and (3), can be expressed as

\[
\begin{align*}
\omega_i(x,t) &= Y_i(x) e^{i\omega t}, \\
Z_i(t) &= Z_i^{(r)} e^{i\omega t},
\end{align*} \tag{20}
\]

where the superscript "r" denotes the mode number and

\[
\begin{align*}
Y_i(x) &= LW_i(\xi), \\
Z_i &= LA_i.
\end{align*} \tag{21}
\]

Substituting (20) into (3) and multiplying the resulting equation by \( Z_i^{(s)} \) yield

\[
\begin{align*}
k_i Z_i^{(r)} Z_i^{(s)} + M_{di} \omega_i^2 Z_i^{(r)} Z_i^{(s)} + \omega_i c_{di} Z_i^{(r)} Z_i^{(s)} &= Y_i^{*(r)} Z_i^{(s)} (k_i + \omega_i c_{di}),
\end{align*} \tag{22}
\]

where \( Y_i^{*(r)} = Y_i^{(r)}(\xi_i) \). Interchanging "r" and "s" in (22) and subtracting the resulting equation from (22) yield

\[
\begin{align*}
\left(\omega_i^2 - \omega_j^2\right) M_{di} Z_i^{(r)} Z_j^{(s)} + c_{di} (\omega_i - \omega_j) Z_i^{(r)} Z_j^{(s)} &= k_i \left( Y_i^{*(r)} Z_j^{(s)} - Y_i^{*(s)} Z_j^{(r)} \right) \\
&+ c_{di} \left( \omega_i Y_i^{*(r)} Z_j^{(s)} - \omega_j Y_i^{*(s)} Z_j^{(r)} \right).
\end{align*} \tag{23}
\]

With reference to the equations of motion of the beam, substituting (20) into (2), then multiplying the resulting equation by \( Y_i^{(s)} \), and integrating over the entire length of the beam, as well as applying the continuity conditions, (12)–(15), with any classical boundary conditions except those for free ends yield

\[
\begin{align*}
\omega_i^2 &\sum_{j=1}^{N} \left( m \int_0^{L_i} Y^{(r)} Y_i^{*(s)} dx + M_{di} Y_i^{*(r)} Y_i^{(s)} \right) \\
&+ \omega_j \sum_{j=1}^{N} c_{di} Y_j^{*(r)} Y_j^{(s)} \\
&= - \sum_{j=1}^{N} \left( EI \int_0^{L_i} Y_i^{(r)} Y_j^{*(r)} dx \right) + k_i Y_j^{*(s)} Y_j^{(r)} \\
&- k_i Z_j^{(r)} Y_j^{*(s)} - c_{di} \omega_j Z_j^{(r)} Y_j^{*(s)}).
\end{align*} \tag{24}
\]

Rewriting (24) and interchanging "r" and "s" yield

\[
\begin{align*}
\omega_i^2 &\sum_{j=1}^{N} \left( m \int_0^{L_i} Y_i^{(r)} Y_i^{*(r)} dx + M_{di} Y_i^{*(r)} Y_i^{(s)} \right) \\
&+ \omega_j \sum_{j=1}^{N} c_{di} Y_i^{*(r)} Y_i^{(s)} \\
&= - \sum_{j=1}^{N} \left( EI \int_0^{L_i} Y_i^{(r)} Y_j^{*(r)} dx \right) + k_i Y_j^{*(r)} Y_j^{(r)} \\
&+ T \int_0^{L_i} Y_i^{(r)} Y_j^{*(r)} dx + k_i Y_j^{*(r)} Y_j^{(r)} \\
&- k_i Z_j^{(r)} Y_j^{*(r)} - c_{di} \omega_j Z_j^{(r)} Y_j^{*(r)}).
\end{align*} \tag{25}
\]

Subtracting (25) from (24) and substituting (23) into the resulting equation yield

\[
\begin{align*}
\omega_i^2 - \omega_j^2 &\sum_{j=1}^{N} \left( m \int_0^{L_i} Y_i^{(r)} Y_j^{*(s)} dx + M_{di} Y_i^{*(r)} Y_j^{(s)} \right) \\
&+ M_{di} Z_i^{(r)} Z_j^{(s)} \\
&+ \omega_j \sum_{j=1}^{N} c_{di} \left( Y_i^{*(r)} Y_j^{*(s)} + Z_i^{(r)} Z_j^{(s)} \right) = 0.
\end{align*} \tag{26}
\]
From (26), the first set of orthogonality relation is obtained as
\[
\sum_{i=1}^{N} \left( m \int_{0}^{L_i} Y_i^{(r)}(r) dx + M_{ci} Y_i^{(r)*} Y_i^{(s)} + M_{ai} Z_i^{(r)} Z_i^{(s)} \right) = \delta_{rs},
\]
(27)
where \( \delta_{rs} \) is the Kronecker delta. The second set of orthogonality relation is expressed as
\[
\sum_{i=1}^{N} (Y_i^{(r)} Y_i^{(s)*} + Z_i^{(r)} Z_i^{(s)*}) = \delta_{rs}.
\]
(28)
The use of (22) and (25) with the aid of some algebraic manipulation yields the third and fourth set of orthogonality relations. This may be written as
\[
\sum_{i=1}^{N} \left( EI \int_{0}^{L_i} Y_i^{(r)*}(r) Y_i^{(s)}(r) dx + T \int_{0}^{L_i} Y_i^{(r)}(s) Y_i^{(s)}(r) dx \right) + \sum_{i=1}^{N} k_i \left( Y_i^{(r)*} Y_i^{(s)} - Z_i^{(r)} Y_i^{(s)*} - Z_i^{(r)*} Y_i^{(s)} + Z_i^{(r)} Z_i^{(s)*} \right) = \delta_{rs},
\]
(29)
\[
\sum_{i=1}^{N} (Y_i^{(r)*} Z_i^{(s)} + Z_i^{(r)*} Y_i^{(s)}) = \delta_{rs}.
\]
(30)

5. Forced Vibration

Assume a harmonic force \( F(x, t) \) is arbitrarily applied along the span of the beam as depicted in Figure 1. The response of the loaded beam is now derived using the generalized orthogonality relations (27)–(30). Let the excitation force be applied at a location \( a_f \) from the left-hand end on the beam; the governing equations of motion are now
\[
m \ddot{w}_i + EI \dddot{w}_i - Tw_i'' = F(x, t) \delta(x - a_f),
\]
(31)
\[
M_{ai} \ddot{z}_i + k_i (z_i - w_i(L_i)) + c_i (\dot{z}_i - \dot{w}_i(L_i)) = 0.
\]
(32)
Using the assumed mode method, the transverse displacement of the beam and the displacement of vibration absorber may be expressed as
\[
w_i = \sum_{r=1}^{N_t} q_r(t) Y_i^{(r)}(x),
\]
(33)
\[
z_i = \sum_{r=1}^{N_t} q_r(t) Z_i^{(r)},
\]
(34)
where \( N_t \) is the number of retained modes, \( Y_i^{(r)}(x) \) is the mode shape corresponding to the \( r \)th mode, \( Z_i^{(r)} \) is the displacement amplitude of the absorber, and \( q_r(t) \) is the \( r \)th generalized coordinate. Substituting (33) and (34) into (31) and (32), respectively, yields
\[
m \sum_{r=1}^{N_t} \ddot{q}_r Y_i^{(r)} + EI \sum_{r=1}^{N_t} \dddot{q}_r Y_i^{(r)*} - T \sum_{r=1}^{N_t} q_r Y_i^{(r)} = F_t \delta(x - a_f),
\]
(35)
\[
M_{ai} \ddot{q}_r + k_i (q_r - z_i) + c_i (\dot{q}_r - \dot{z}_i) = 0.
\]
(36)
Use of the orthogonality relations, (27)–(30), yields the following uncoupled differential equation:
\[
[M_{rr}] [\ddot{q}_r] + [C_{rr}] [\dot{q}_r] + [K_{rr}] [q_r] = \{F_r\},
\]
(37)
where the matrices \( M_{rr}, C_{rr}, \) and \( K_{rr} \) are expressed as
\[
M_{rr} = \sum_{i=1}^{N} \left( m \int_{0}^{L_i} Y_i^{(r)*}(r) Y_i^{(r)}(r) dx + M_{ci} Y_i^{(r)*} Y_i^{(s)} + M_{ai} Z_i^{(r)} Z_i^{(s)} \right),
\]
\[
C_{rr} = \sum_{i=1}^{N} c_i (Y_i^{(r)*} Z_i^{(s)} - Z_i^{(r)} Y_i^{(s)*}),
\]
\[
K_{rr} = \sum_{i=1}^{N} \left\{ \int_{0}^{L_i} \left( EI Y_i^{(r)*}(r) Y_i^{(s)}(r) dx + k_i (Y_i^{(r)*} - Z_i^{(r)}) \right)^2 \right\},
\]
\[
F_r = F(x, t) Y_i^{(r)}(a_f).
\]
(38)
The amplitude of the vibration absorber can be readily expressed as

$$Z_{ii}^{(r)} = \kappa_i Y_{ii}^{(r)},$$

$$\kappa_i = \left(1 + \left(2\gamma r_i\right)^2 \over \left(1 - r_i^2\right)^2 + \left(2\gamma r_i\right)^2 \right)^{1/2},$$

$$\varsigma_i = \frac{c_{di}}{2M_d \omega_{ii}}, \quad \omega_{ii} = \frac{k_i}{M_{ii}}.$$

### 6. Numerical Simulation

The sets of parameters employed in the numerical examples are taken from [1, 16]; they are tabulated in Table 1. The validity of the free vibration of the present model is inferred from the results tabulated in Table 2. In the case of a cantilevered beam with three spring-mass-damper systems, the first five natural frequencies of the present model are compared to those of [16]. The results show very good agreement with a maximum error of 0.28%.

With respect to a pinned-pinned beam with attached three and five spring-mass systems, the validation is done via [1] and shows excellent agreement with four decimal places. The corresponding mode shapes for a beam carrying the three in-span spring-mass systems are depicted in Figure 2. This figure is identical to Figure 3 from [1].

For the forced vibration simulations, an excitation force of $F(t) = 10 \sin(\Omega t)$ is used with zero initial conditions. The force is first applied at the free end of a cantilevered beam with three identical spring-mass-damper systems located at 0.1, 0.5, and 0.9 m from the clamp end. The time history of the vertical displacement of the free end is presented to serve for comparison between the proposed approach (i.e., the combination of the generalized orthogonality conditions with the exact mode shapes of the loaded beam), the finite element method (FEM), and the approach used in [16]. The results are depicted in Figures 3 and 4 for an excitation frequency of 5 and 10 rad/s, respectively. All three methods are in agreement, but the FEM results agree better with the present approach than that of [16].

The frequency response curves for a simply supported beam with one in-span mass-spring-damper-mass system attached at 0.1 m from one end using three approaches are depicted in Figure 5. The first approach, which is the most accurate [25], employs the generalized orthogonality conditions along with the mode shapes of the loaded beam. The classical orthogonality relations and the mode shapes of the loaded beam are employed in the second approach, such as in [17–20]. The third method also uses the classical orthogonality conditions, but the mode shapes are those of the bare beam (see [14–16]). All three approaches yield very different midspan vertical displacements. The first approach is the exact solution and hence the error associated with the difference is defined with respect to the first approach. The frequency response amplitude errors are depicted in Figure 6 where the error can be as high as $10^4$.  

### Table 1: Material properties and parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference [1]</th>
<th>Reference [16]</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$EI$</td>
<td>63476.1</td>
<td>36.4583</td>
<td>Nm²</td>
</tr>
<tr>
<td>$L$</td>
<td>1.0</td>
<td>1.0</td>
<td>m</td>
</tr>
<tr>
<td>$m$</td>
<td>15.385</td>
<td>0.675</td>
<td>kg/m</td>
</tr>
<tr>
<td>$m_1$</td>
<td>3.0775</td>
<td>0.1</td>
<td>kg</td>
</tr>
<tr>
<td>$m_2$</td>
<td>4.614</td>
<td>0.1</td>
<td>kg</td>
</tr>
<tr>
<td>$m_3$</td>
<td>7.69</td>
<td>0.1</td>
<td>kg</td>
</tr>
<tr>
<td>$m_4$</td>
<td>9.997</td>
<td>—</td>
<td>kg</td>
</tr>
<tr>
<td>$m_5$</td>
<td>15.38</td>
<td>—</td>
<td>kg</td>
</tr>
<tr>
<td>$k_1$</td>
<td>190428</td>
<td>0.1</td>
<td>N/m</td>
</tr>
<tr>
<td>$k_2$</td>
<td>222166</td>
<td>0.1</td>
<td>N/m</td>
</tr>
<tr>
<td>$k_3$</td>
<td>285642.45</td>
<td>0.1</td>
<td>N/m</td>
</tr>
<tr>
<td>$k_4$</td>
<td>317380</td>
<td>—</td>
<td>N/m</td>
</tr>
<tr>
<td>$k_5$</td>
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<td>N/m</td>
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<tr>
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<td>—</td>
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</tr>
<tr>
<td>$c_{d2}$</td>
<td>—</td>
<td>—</td>
<td>Ns/m</td>
</tr>
<tr>
<td>$c_{d3}$</td>
<td>—</td>
<td>—</td>
<td>Ns/m</td>
</tr>
</tbody>
</table>

![Figure 2](image2.png)

**Figure 2:** Mode shapes of a simply supported beam carrying three in-span spring-mass systems using the same parameters from [1].

![Figure 3](image3.png)

**Figure 3:** Time history of the free-end vertical displacement for a cantilevered beam carrying three mass-spring-damper systems for a forcing frequency $\Omega = 5$ rad/s, $k = 0.1$ N/m, $T = 0$, $M_1 = 0.1$ kg, $M_i = 0$ kg, $c_d = 0.1$ Ns/m, and $L = 1.2, 3 = 0.1, 0.5, 0.9$ m.
Table 2: Natural frequency validation (rad/s).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cantilevered 3 spring-mass-damper</th>
<th>Pinned-pinned 3 spring-mass</th>
<th>Pinned-pinned 5 spring-mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-0.367 \pm 25.8769i$</td>
<td>$-0.367 \pm 25.8544i$</td>
<td>$152.7339$</td>
</tr>
<tr>
<td>2</td>
<td>$-0.274 \pm 161.7655i$</td>
<td>$-0.275 \pm 161.9399i$</td>
<td>$185.0949$</td>
</tr>
<tr>
<td>3</td>
<td>$-0.031 \pm 452.1367i$</td>
<td>$-0.031 \pm 452.4320i$</td>
<td>$247.8313$</td>
</tr>
<tr>
<td>4</td>
<td>$-0.171 \pm 887.2157i$</td>
<td>$-0.174 \pm 887.3469i$</td>
<td>$677.5959$</td>
</tr>
<tr>
<td>5</td>
<td>$-0.081 \pm 1467.5170i$</td>
<td>$-0.082 \pm 1468.8356i$</td>
<td>$2548.6572$</td>
</tr>
</tbody>
</table>

Figure 4: Time history of the free-end vertical displacement for a cantilevered beam carrying three mass-spring-damper systems for a forcing frequency $\Omega = 10$ rad/s, $k = 0.1$ N/m, $T = 0$, $M_d = 0.1$ kg, $M_c = 0$ kg, $c_d = 0.1$ Ns/m, and $L_{1,2,3} = 0.1, 0.5, 0.9$ m.

Figure 5: Frequency response of a simply supported beam carrying one in-span mass-spring-damper-mass system for $k = 10$ N/m, $M_d = 0.1$ kg, $M_c = 0.05$ kg, $T = 360$ N, $EI = 36.458$ Nm$^2$, $c_d = 0.1$ Ns/m, and $L_d = 0.1$ m.

Figure 6: Frequency response amplitude error for a simply supported beam carrying one in-span mass-spring-damper-mass system for $k = 10$ N/m, $M_d = 0.1$ kg, $M_c = 0.05$ kg, $T = 360$ N, $EI = 36.458$ Nm$^2$, $c_d = 0.1$ Ns/m, and $L_d = 0.1$ m.

Figure 7 is an identical plot to Figure 5 with the pinned-pinned configuration replaced by a guided-guided one. The corresponding frequency response amplitude error is shown in Figure 8. The maximum amplitude error for the guided-guided beam is higher than that for the simply supported beam. A similar observation with regard to the discrepancy associated with the use of the classical orthogonality was reported in [25] for a simply supported beam carrying a heavy mass. An error as high as $10^{-5}$ was reported.

The three approaches are also examined using the parameters taken from [1] for a simply supported beam with one in-span mass-spring-damper system and no tension. Figures 9 and 10 show the frequency response of the midspan displacement for a damping coefficient $c_{di} = 0.1$ Ns/m and $c_{di} = 100$ Ns/m, respectively. It can be observed that all three methods yield very similar results and the plots are barely distinguishable. The amplitude errors associated with the results presented in Figures 9 and 10 are depicted in Figures 11 and 12, respectively. But for excitation frequencies closer to 600 rad/s the results indicate very minimal error. The discrepancy is more pronounced in the case of the classical orthogonality with the combination of the bare beam mode shapes.

7. Conclusions

A common approach to studying the vibrational response of an elastically loaded beam involves the use of the classical...
orthogonality relations along with the mode shapes of the bare beam. It has been shown, however, that the mode shapes of the bare beam can be quite different from those of the loaded beam. In the present paper, the exact natural frequencies and mode shapes were presented for an axially loaded beam carrying several vibration absorbers. Explicit expressions were presented for the generalized orthogonality condition. The obtained generalized orthogonality relation was employed along with the assumed modes method to study the forced vibrational response. The numerical simulations indicated that using the common approach could produce erroneous results. The combination of the exact mode shapes of the loaded beam and the corresponding generalized orthogonality relation is necessary for accurate dynamic modeling of a beam carrying elastically mounted masses with dampers.
Appendix

For the sake of simplicity, the following notations are used:

\[
\begin{aligned}
    s_\alpha &= \sin \alpha, & c_\alpha &= \cos \alpha, \\
    sh_\beta &= \sinh \beta, & ch_\beta &= \cosh \beta, \\
    s_{\alpha i} &= \sin \alpha (\xi_i), & c_{\alpha i} &= \cos \alpha (\xi_i), \\
    sh_{\beta i} &= \sinh \beta (\xi_i), & ch_{\beta i} &= \cosh \beta (\xi_i), \\
    e &= K_1 y_1 - \eta_1.
\end{aligned}
\]

The elements of the matrix \( \mathcal{F} \) are expressed as

\[
\mathcal{F}_{(4i-1,4i-1)} = s_{\alpha i}, \quad \mathcal{F}_{(4i-1,4i-2)} = c_{\alpha i}, \\
\mathcal{F}_{(4i-1,4i-3)} = sh_{\beta i}, \quad \mathcal{F}_{(4i-1,4i-4)} = ch_{\beta i}.
\]

The elements for the cantilevered beam with one in-span mass-spring-mass support is obtained by taking the determinant of the following matrix:

\[
\begin{bmatrix}
    0 & 1 & 0 & 0 & 0 \\
    1 & 0 & 0 & 0 & 0 \\
    s_{\alpha 1} & c_{\alpha 1} & sh_{\beta 1} & -s_{\alpha 1} & -c_{\alpha 1} \\
    c_{\alpha 1} & -s_{\alpha 1} & ch_{\beta 1} & -c_{\alpha 1} & -s_{\alpha 1} \\
    -\alpha^2 s_{\alpha 1} & -\alpha^2 c_{\alpha 1} & \beta^2 ch_{\beta 1} & -\alpha^2 s_{\alpha 1} & -\alpha^2 c_{\alpha 1} \\
    -\alpha^3 c_{\alpha 1} + \epsilon s_{\alpha 1} & \alpha^3 s_{\alpha 1} + \epsilon c_{\alpha 1} & \beta^2 ch_{\beta 1} + e sh_{\beta 1} & \beta^3 ch_{\beta 1} + e ch_{\beta 1} & \beta^3 s_{\alpha 1} \\
    0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References


