Overall Design and Experimental Verification of Piezoelectric Smart Structures for Vibration and Noise Control

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X Summary
Objectives of the Smart Systems Group at the Mechanics Institute

- Vibration and noise control, shape control
- Modelling, simulation, overall design tools
- Experimental verification (hardware-in-the-loop realization) and applications
Vibration and noise suppression under different operation conditions

Virtual Systems Design
1. Selection of appropriate actuators and sensors
2. Optimal placement of actuators and sensors at the structure
3. Design of the controller
4. Overall virtual simulation of the system
5. Optimisation of the system
6. Hardware-in-the-loop experiments
Tools for the virtual development process

**Large movements**
- MBS (SIMPACK)

**Small deformations**
- FEM (COSAR, ANSYS, ABAQUS, ...)

**Actuators/Sensors**
- PZT, PVDF
- SMA
- MRF, ERF
- Functional Gels
- Optical Fibres
- ... (FORTRAN-Unterprogramme)

**Adaptronics**
- Control (Matlab/SIMULINK)

**CAD**
Finite element analysis of piezoelectric smart structures

Constitutive Equations

\[ T_{ik} = C_{iklm}^{E} S_{lm} - e_{lik} E_{l} - \lambda_{ik}^{E} \theta \]

\[ D_{i} = e_{ilm} S_{lm} + \varepsilon_{il}^{E} E_{l} + \pi_{i}^{E} \theta \]

\( T \) – stresses, 
\( D \) – el. displacements
\( S \) – strains, 
\( E \) – electric field

Transversal isotropic piezoelectric materials

3D constitutive equations

\[
 C = \begin{bmatrix}
 c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\
 c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\
 c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\
 c_{66} & 0 & 0 & c_{44} & 0 & 0 \\
 & & & & & 0 \\
 & & & & & 0 \\
\end{bmatrix}
\]

\[
 \mathbf{e} = \begin{bmatrix}
 0 & 0 & e_{31} \\
 0 & 0 & e_{31} \\
 0 & 0 & e_{33} \\
 0 & e_{15} & 0 \\
 e_{15} & 0 & 0 \\
\end{bmatrix}
\]

\[
 \mathbf{\varepsilon} = \begin{bmatrix}
 \varepsilon_{11} & 0 & 0 \\
 0 & \varepsilon_{11} & 0 \\
 0 & 0 & \varepsilon_{33} \\
\end{bmatrix}
\]

transformation of material matrices
for arbitrary directions
Balance equations

\[
\begin{align*}
\text{div } \mathbf{\sigma} + \rho \mathbf{b} - \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} &= 0 \\
\text{div } \mathbf{D} &= 0 \\
\text{div } \mathbf{q} - \rho r + \Theta \rho \dot{\eta} &= 0
\end{align*}
\]

Weak form of the balance equations

\[
\int_{V} (\text{div } \mathbf{\sigma} + \rho \mathbf{b} - \rho \frac{\partial^2 \mathbf{u}}{\partial t^2}) \delta \mathbf{u} \, dV + \int_{V} (\text{div } \mathbf{D}) \delta \phi \, dV + \int_{V} (\text{div } \mathbf{q} - \rho r + \Theta \rho \dot{\eta}) \delta \theta \, dV + \ldots \text{BCs} \ldots = 0
\]
Approximation of the unknown fields

Displacements: \( u_i = \sum_{L=1}^{M^{(me)}} N_L^{(me)} u_{iL} \)
Electric potential: \( \phi = \sum_{L=1}^{M^{(cl)}} N_L^{(cl)} \phi_L \)

Temperature: \( g = \sum_{L=1}^{M^{(th)}} N_L^{(th)} g_L \)

Semi-discrete form of the equations of motion:

\[
\begin{bmatrix}
M_{uu} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{u} \\
\dot{\phi} \\
\dot{g}
\end{bmatrix} +
\begin{bmatrix}
R_{uu} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{u} \\
\dot{\phi} \\
\dot{g}
\end{bmatrix} +
\begin{bmatrix}
K_{uu} & K_{u\phi} & -K_{u\phi} \\
K_{u\phi} & -K_{\phi\phi} & K_{\phi\phi} \\
0 & 0 & K_{g\phi}
\end{bmatrix}
\begin{bmatrix}
u \\
\phi \\
g
\end{bmatrix} =
\begin{bmatrix}
f_u \\
f_\phi \\
f_g
\end{bmatrix}
\]
Coupling with the acoustic field

The basis is the linear acoustic wave equation (small perturbations related to an ambient reference state)

\[ \Delta p = \frac{1}{c^2} \ddot{p} \]

With the velocity potential \( \Phi \), which is a scalar field related to the velocity as \( \mathbf{v} = -\mathbf{D}_a \Phi \)

of the fluid particles the pressure can be written as \( p = \rho_0 \dot{\Phi} \). This results in

\[ \Delta \Phi = \frac{1}{c^2} \ddot{\Phi} \]

The weak form of the acoustic wave equation results in

\[
\chi = -\frac{1}{c^2} \int f \delta \Phi \dddot{\Phi} dV - \frac{\rho_0}{Z} \int \delta \Phi \dddot{\Phi} dO - \int \delta \Phi \mathbf{D}_a^T \mathbf{D}_a \dddot{\Phi} dV - \int \delta \Phi \mathbf{D}_a^T dO \mathbf{D}_a \dddot{\Phi} = 0
\]

\[
\mathbf{D}_a^T = \begin{bmatrix}
\frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z}
\end{bmatrix}
\]
The velocity of the vibrating structure acts as an acoustic load of the fluid. The normal velocity of the structure can be expressed as \( \dot{u}_n = \mathbf{n}^T \mathbf{N}_w \ddot{\mathbf{w}} \)

\[
\begin{bmatrix}
M_{ww} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -\rho_0 M_a
\end{bmatrix}
\begin{bmatrix}
\ddot{\mathbf{w}} \\
\ddot{\phi}
\end{bmatrix}
+ \begin{bmatrix}
C_{ww} & 0 & -C_{wc} \\
0 & 0 & 0 \\
-C_{wc}^T & 0 & -\rho_0 (C_a + C_f)
\end{bmatrix}
\begin{bmatrix}
\dot{\mathbf{w}} \\
\dot{\phi}
\end{bmatrix}
+ \begin{bmatrix}
K_{ww} & K_{w\phi} & 0 \\
K_{w\phi}^T & -K_{\phi\phi} & 0 \\
0 & 0 & -\rho_0 (K_a + K_f)
\end{bmatrix}
\begin{bmatrix}
\mathbf{w} \\
\phi \\
\mathbf{\Phi}
\end{bmatrix}
= \begin{bmatrix}
\mathbf{f}_w \\
\mathbf{f}_\phi \\
-\rho_0 \mathbf{f}_a
\end{bmatrix}
\]

With an additional load term due to the fluid pressure:

\[
f_{ac} = -\int_{O_s^{(e)}} N_a^T \mathbf{n}^T \mathbf{N}_w dO \dot{\mathbf{w}} = \frac{1}{\rho_0} C_{wc}^T \ddot{\mathbf{w}}
\]

\[
f_{wc} = \int_{O_s^{(e)}} \mathbf{N}_w^T \mathbf{n} dO = \rho_0 \int_{O_s^{(e)}} \mathbf{N}_w^T \mathbf{n} \mathbf{N}_a dO \dot{\Phi} = C_{wc} \dot{\Phi}
\]
Finite element software for piezoelectric smart systems

3D Truss & Beam) Elements

2D Plan and Axisymmetric Elements

2.5D Layered Shell Elements

3D Continuum Elements

3D Layered Shell Elements

*) siehe www.femcos.de
Modelling piezoelectric fibres

Piezoelectric fiber composites

FhG’s Würzburg, Dresden, Bremen

Draft of a piezoelectric fiber composite
### Calculation of effective coefficients of PZT composites

\[ \begin{bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{23} \\ T_{31} \\ T_{12} \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} C_{11}^{\text{eff}} & C_{12}^{\text{eff}} & C_{13}^{\text{eff}} & 0 & 0 & 0 & 0 & 0 & -e_{13}^{\text{eff}} \\ C_{12}^{\text{eff}} & C_{11}^{\text{eff}} & C_{13}^{\text{eff}} & 0 & 0 & 0 & 0 & 0 & -e_{13}^{\text{eff}} \\ C_{13}^{\text{eff}} & C_{13}^{\text{eff}} & C_{33}^{\text{eff}} & 0 & 0 & 0 & 0 & 0 & -e_{33}^{\text{eff}} \\ 0 & 0 & 0 & C_{44}^{\text{eff}} & 0 & 0 & 0 & -e_{15}^{\text{eff}} & 0 \\ 0 & 0 & 0 & 0 & C_{44}^{\text{eff}} & 0 & -e_{15}^{\text{eff}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^{\text{eff}} & 0 & 0 & 0 \\ 0 & 0 & 0 & e_{15}^{\text{eff}} & 0 & e_{11}^{\text{eff}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e_{15}^{\text{eff}} & 0 & e_{11}^{\text{eff}} & 0 & 0 \\ e_{13}^{\text{eff}} & e_{13}^{\text{eff}} & e_{33}^{\text{eff}} & 0 & 0 & 0 & 0 & 0 & e_{33}^{\text{eff}} \end{bmatrix} \begin{bmatrix} S_{1} \\ S_{2} \\ S_{3} \\ S_{23} \\ S_{31} \\ S_{12} \\ S_{1} \\ S_{2} \\ S_{3} \end{bmatrix} \]

#### 1. Using the third row to calculate

\[ \bar{T}_{33} = C_{33}^{\text{eff}} \bar{S}_{33} \]

#### 2. Using the first row to calculate

\[ \bar{T}_{11} = C_{13}^{\text{eff}} \bar{S}_{33} \]

- \( C_{33}^{\text{eff}} = \frac{\bar{T}_{33}}{\bar{S}_{33}} \)
- \( C_{13}^{\text{eff}} = \frac{\bar{T}_{11}}{\bar{S}_{33}} \)
Piezoelectric fibres made from PZT 5A (N/m², C/m² and F/m)

<table>
<thead>
<tr>
<th></th>
<th>C11 * E10</th>
<th>C 12* E10</th>
<th>C 13 * E10</th>
<th>C 33 * E10</th>
<th>C 44 * E10</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT</td>
<td>12.1</td>
<td>7.54</td>
<td>7.52</td>
<td>11.1</td>
<td>2.11</td>
</tr>
<tr>
<td>e15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e31</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ε11 * E-9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ε33* E-9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PZT</td>
<td>12.3</td>
<td>-5.4</td>
<td>15.8</td>
<td>8.11</td>
<td>7.35</td>
</tr>
</tbody>
</table>

Matrixmaterial: Polymermaterial with E=1.806 E9 N/m², ν= 0.3994

Fibre volume fraction

0.111  0.222  0.333  0.444  0.556  0.667
Example: Results

Selected results compared with calculations based on other methods

![Graphs showing comparison of effective moduli and strain coefficients across fiber volume fraction.](image)

Fiber volume fraction

C_{11}^{\text{eff}} [GPa]

C_{33}^{\text{eff}} [GPa]

Selected results compared with calculations based on other methods.

FEM-SQU
AHM-SQU
FEM-HEX
AHM-HEX

Vol. Fraction

\varepsilon_{13}^{\text{eff}} [\text{GPa}]

Selected results compared with calculations based on other methods.

FEM
AHM

Linz, 7. Oktober 2005

Otto-von-Guericke-Universität Magdeburg
Institut für Mechanik
Ulrich Gabbert:
Overall Design and Experimental Verification of Piezoelectric Smart Structures
for Vibration and Noise Control
Shell type models for piezoelectric composites
Modelling of piezoelectric composites based on CLT

- Basis: Discrete-Kirchhoff Theory (DKT)
- Lagrangian and Legendre polynomials
- Tangential rotations only

Classical SemiLoof shell element
- Quadrilateral element with 32 dof’s
- Triangular element with 24 dof’s
Electromechanical coupling is taken into account.

The piezoelectric layers are assumed to be complete metalized and electrodized, where the electric field $E_{3i}$ is again assumed to be constant over thickness $h_i$: 

$$E_{3i} = \Delta \phi / h$$

The element is enhanced by additional electric potential differences $\Delta \phi_i$ for each active layer $i$. The coupling is taken into account by:

$$
\begin{bmatrix}
K_e^{(mm)} & K_e^{(me)} \\
K_e^{(me)^T} & K_e^{(ee)}
\end{bmatrix}
\begin{bmatrix}
\Delta \phi_e \\
u_e
\end{bmatrix} =
\begin{bmatrix}
f_e^{(m)} \\
f_e^{(e)}
\end{bmatrix}
$$

$$
K_e^{(mm)} = \int_{A_e} B^{(m)^T} C B^{(m)} dA ;
K_e^{(me)} = \int_{A_e} B^{(m)^T} e B^{(e)} dA ;
K_e^{(ee)} = \int_{A_e} B^{(e)^T} \kappa B^{(e)} dA
$$

The assumption of the electric field has been intensively investigated!
Controller design

\[
M \ddot{q} + D_d \dot{q} + Kq = \bar{E} f(t) + \bar{B} u(t)
\]

Model reduction (e.g. modal space):

\[q = \Phi z\]

State space representation:

\[
x^T = [z \quad \dot{z}]^T
\]

\[
\begin{bmatrix}
0 & 1 \\
-\Lambda_r & -\Delta_r
\end{bmatrix} x(t) +
\begin{bmatrix}
0 \\
\Phi_r^T \Phi
\end{bmatrix} u(t) +
\begin{bmatrix}
0 \\
\Phi_r^T E
\end{bmatrix} f(t)
\]

\[
\dot{x} = Ax + Bu + Ef
\]

\[
y = Cx + Du + Ff
\]
Data exchange FEA and controller design software

FE system COSAR

\[ M\ddot{q} + D\dot{q} + Kq = E\dot{f}(t) + B\dot{u}(t) \]

- Eigenvalue analysis, modal reduction and transformation into the state space form
- \[ \ddot{x} = Ax + Bu(t) + Ef(t) \]
- \[ y = Cx + Du(t) + Ff(t) \]

FE / control interface

Modal state space matrices
A, B, C, D, E, F

Controller matrix
L

Matlab/Simulink

Controller design

\[ u(t) = -Lx \]
LQ-Controller with observer and additional dynamics

Discrete-time tracking system

\[ r[k] \rightarrow \Sigma \rightarrow \Phi, \Gamma, L_2 \rightarrow \Sigma \rightarrow \Phi x[k] + \Gamma u[k] + \varepsilon f[k] \]

\[ y[k] = C x[k] \]

\[ \hat{x}[k] = \bar{x}[k] + L_{oo}(y[k] - C\bar{x}[k]) \]

\[ \bar{x}[k+1] = \Phi \hat{x}[k] + \Gamma u[k] \]

\[ \Sigma \rightarrow \hat{x}[k] \]

\[ \hat{u}[k] \]

\[ f[k] \rightarrow \Sigma \rightarrow y[k] \]

I) Discrete continuous optimization (gradient based methods)
[see the Weber/Gabbert (1998,99); Schulz/Gabbert(2001)]

II) Controllability and observeability index
[see Seeger/Köppe/Gabbert (2002)]

III) Continuous optimization (gradient based methods)
[see Seeger/Gabbert (2003)]

IV) Evolutionary optimization
[see Bohn/Gabbert (2004), WCCM VI]
Automatic integration of a patch mesh in a base mesh

- Projection of the FE-mesh of the piezoelectric patch into the host structure
- Identification of overlapping elements
- Local remeshing of the host structure with embedded piezoelectric patch
Sensitivity

Accuracy
Objective function: accuracy sufficient with mesh a) and b)
Gradients: accuracy not sufficient with mesh a)
accuracy sufficient with mesh b)

see: F. Seeger, PhD thesis, Uni Magdeburg, VDI Düsseldorf, 2004
Gradient based optimisation in the frequency domain

Starting point is the state space formulation

\[
\dot{z}(t) = \begin{bmatrix} 0 & I \\ -\Lambda & -\Delta \end{bmatrix} z(t) + \begin{bmatrix} 0 \\ \Phi^T B \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ \Phi^T E \end{bmatrix} f(t) = Az + Bu(t) + Ef(t)
\]

\[
y = Cz
\]

Transformation in the frequency domain results in

\[
j \omega Z(j \omega) = AZ(j \omega) + BU(j \omega) + EF(j \omega)
\]

\[
Y(j \omega) = CZ(j \omega)
\]

Introducing a controller in the form of \( U(j \omega) = -KZ(j \omega) \) results in

\[
Y(j \omega) = C(j \omega I - A + BK)^{-1} EF(j \omega)
\]

\[
= H(j \omega) F(j \omega)
\]
The transfer function can be calculated by solving the linear system of equations

\[(j\omega I - A + BK)\hat{Z}(j\omega) = E\]

\[H(j\omega) = C\hat{Z}(j\omega)\]

For the optimization based on the frequency response function an objective function can be created, such as

\[J_F = \frac{1}{\omega_b - \omega_a} \int_{\omega_a}^{\omega_b} \|H\|^2 d\omega.\]

In the gradient based optimization the gradients are required:

\[\frac{\partial J_F}{\partial p} = \frac{1}{\omega_b - \omega_a} \int_{\omega_a}^{\omega_b} \frac{\partial}{\partial p} \|H\|^2 d\omega\]

\[\frac{\partial H}{\partial p} = \frac{\partial C}{\partial p} \hat{Z} + C \frac{\partial \hat{Z}}{\partial p}.\]
Test example: Optimal actuator and sensor positioning

Clamped plate:
Two actuators to controlling the eigenmodes in a given frequency band

- 1: 0-600 Hz
- 2: 150-350 Hz
- 3: 275-325 Hz

E: External forces
K: Clamped plate
Test example: Results

- no control
- 0: Start
- 1: 0-600 Hz
- 2: 150-350 Hz
- 3: 275-325 Hz
Modal Controllability Index

\[ \mu_k = \phi_k^T B \, B^T \phi_k \]

This index can be quite simple evaluated based on a finite element model. It can be seen as the signal (voltage of a patch actuator at one point of the mesh, if the structure is excited in one eigenmode). For one mesh point \( i \) and the \( k^{\text{th}} \) eigenmode we receive:

\[ \mu_{ki} = \phi_{ki}^2 \]

Example 3: Clamped plate
Modal controllability indices of the first five modes of a rectangular clamped plate

Optimal actuator positions
Test example 3: Experimental setup

A smart clamped plate

Thin plate made of Al (or steel, or GFC)

Thin ceramic patches made of PZT

Connection between the ceramic patches and the control unit
Test example: Measurement, impulse excitation and LQ-controller

Impulse excitation

Amplitudengang Impulsbelastung - Sensor 1

Frequency [Hz]

Amplitude [dB]

- ungeregelt
- geregelt
- geregelt+kompens.
Test example: Optimal angel of patch actuator
Test example: Acoustic box

Excitation with a sin-signal containing the first two eigenfrequencies of the system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus $E$</td>
<td>210000 N/mm²</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$</td>
<td>0.3</td>
</tr>
<tr>
<td>Density $\rho_p$</td>
<td>2.63 $\cdot$ 10^{-9} Ns²/mm⁴</td>
</tr>
<tr>
<td>Speed of sound $c$</td>
<td>340000 mm/s</td>
</tr>
<tr>
<td>Fluid density $\rho_0$</td>
<td>1.29 $\cdot$ 10^{-12} Ns²/mm⁴</td>
</tr>
</tbody>
</table>

Plate/Cavity System

- $l_1$: 600 mm (Length in $x_1$-direction)
- $l_2$: 400 mm (Length in $x_2$-direction)
- $l_3$: 400 mm (Patch thickness)
- $h$: 2 mm (Plate thickness)

Boundary Conditions (BC): Bottom: $p=0$, Sidewalls: $v=0$

Excitation with a sin-signal containing the first two eigenfrequencies of the system

<table>
<thead>
<tr>
<th>Elastic Constants</th>
<th>Piezoelectric Constants</th>
<th>Dielectric Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{11}$ 107600 N/mm²</td>
<td>$e_{15}$ 1.20 $\cdot$ 10^{-5} N/(mV)mm</td>
<td>$\kappa_{11}$ 1.74 $\cdot$ 10^{-14} N/(mV)²</td>
</tr>
<tr>
<td>$c_{12}$ 63120 N/mm²</td>
<td>$e_{31}$ -9.60 $\cdot$ 10^{-6} N/(mV)mm</td>
<td>$\kappa_{33}$ 1.87 $\cdot$ 10^{-14} N/(mV)²</td>
</tr>
<tr>
<td>$c_{13}$ 63850 N/mm²</td>
<td>$e_{33}$ 1.51 $\cdot$ 10^{-5} N/(mV)mm</td>
<td>Density $\rho$ 7.80 $\cdot$ 10^{-9} Ns²/mm⁴</td>
</tr>
</tbody>
</table>
Test example: Acoustic box, results

- Sensor signal
- Sound pressure

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Industrial example: Active vibration control of a MRT

Funnel of a Siemens MRT

Eigenfrequencies of Interest

FEA-model for optimizing the Actuator/sensor position
Active vibration reduction of a funnel of a MRT
Hardware-in-the-loop experiments

The scheme of the funnel experimental rig for the modal analysis
Active vibration reduction of a funnel of a MRT

Measured and identified Frequency Response Functions for actuator/sensor pairs A1R-S1L

A2R-S1R

A1R-S1L

![Measured and identified Frequency Response Functions](image-url)
Optimal LQ control

Active vibration reduction of a funnel of a MRT

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Industrial Example: Control of the first eigenfrequency

Actuator/sensor pairs A2R–S1R

Actuator/sensor pairs A1R–S1L
Summary

- In the presentation it was shown, that an overall virtual development approach to design and to evaluate smart structures concepts is required.

- For smart structures design a finite element approach coupled with controller design software Matlab/Simulink was discussed.

- For piezoelectric fibre composites a homogenisation technique based on a RVE approach to evaluate effective material properties was presented.

- For thin-walled structures shell type finite elements were shown, which are an effective approach for an overall design procedure.

- In controller design we have used model based optimal LQ (FE-model and/or identified model) with Kalman estimator and additional dynamics, which was briefly discussed only.

- For calculating best positions of actuators/sensors at structures a gradient based optimization was presented. But simpler methods based on a modal criterion have shown to result in a first acceptable solution.

- The design procedure was applied to several test cases and industrial applications, where also hardware-in-the-loop realizations have been performed to evaluate the results.

- Recent activities are also focused on smart machine systems, which perform large motion, where as design basis an multi-body systems (MBS) approach is used.