An Investigation Into the Effect of the PCB Motion on the Dynamic Response of MEMS Devices Under Mechanical Shock Loads

Fadi Alsalem
Mohammad I. Younis

e-mail: myounis@binghamton.edu

Ronald Miles

Department of Mechanical Engineering, State University of New York at Binghamton, Binghamton, NY 13902

Received: 9 January 2007; revised: 14 January 2008; published: 29 July 2008

We present an investigation into the effect of the motion of a printed circuit board (PCB) on the response of a microelectromechanical system (MEMS) device to shock loads. A two-degrees-of-freedom model is used to model the motion of the PCB and the microstructure, which can be a beam or a plate. The mechanical shock is represented as a single point force impacting the PCB. The effects of the fundamental natural frequency of the PCB, damping, shock pulse duration, electrostatic force, and their interactions are investigated. It is found that neglecting the PCB effect on the modeling of MEMS under shock loads can lead to erroneous predictions of the microstructure motion. Further, contradictory to what is mentioned in literature that a PCB, as a worst-case scenario, transfers the shock pulse to the microstructure without significantly altering its shape or intensity, we show that a poor design of the PCB or the MEMS package may result in severe amplification of the shock effect. This amplification can cause early pull-in instability for MEMS devices employing electrostatic forces.

Contents

- Background
  - A MEMS Response Under Shock Load (Without Including the Assembly Effect)
  - B MEMS Response Under Shock Load (Including the Assembly Effect)
  - C Electronic Equipment Response Under Shock Load
  - D Electrostatic MEMS Devices
- Problem Formulation
- Results
  - A Undamped Response
  - B Damped Response
  - C Comparison Between a Continuous-Lumped Model With the 2DOF Model of a Clamped-Clamped Beam
- Effect of Electrostatic Forces
- Summary and Conclusions
- Future Work
- Acknowledgement
- REFERENCES
- FIGURES

Background

Recently, there has been considerable interest in the reliability research on microelectromechanical system (MEMS) under shock and vibration effects. This has been boosted by the development of portable devices containing MEMS devices. A MEMS device can be exposed to shock loads during fabrication, assembly process, while transporting, and in service. Short circuits, stiction, and fracture are common problems caused by mechanical shock, which lead to failure of MEMS devices. A rigorous analysis of the response of MEMS devices under shock represents a key issue for their growth and commercialization.

At least four levels of assembly (packaging) can be defined in MEMS devices. Level 1 involves the connection between a microstructure and a substrate, Level 2 represents the bonding between the silicon substrate and a chip, Level 3 involves the connection of the leads from the chip carrier to a printed circuit board (PCB), and Level 4 represents the connection of the PCB to a supported structure. The microstructure is required to be attached to the substrate almost rigidly. This requirement is very important because sensing is usually achieved electrostatically, which is very sensitive to the substrate movement.

Several studies have been conducted on the effect of shock loads applied directly on a MEMS device. However, less attention has been given to the shock effect on the MEMS device accounting for assembly effect. Recently, considerable research has been directed to the electronic equipment reliability under shock loads considering assembly effect. Because MEMS and electronic devices often share the same high levels of assembly (chip, PCB, and chassis), it is vital to review the contributions made on the reliability of electronic devices to develop a better understanding of the MEMS response under shock loads including assembly effects. In the following we review some of the contributions in the related areas.

A.MEMS Response Under Shock Load (Without Including the Assembly Effect). Many authors have studied the MEMS response under shock loads without incorporating the assembly effect. For example, studied the response of a MEMS accelerometer to a shock load induced by drop test. They used a beam theory and finite-element analysis to calculate the stress history of the device during impact. solved analytically the equation of motion for the maximum deflection of a microstructure under drop test and calculated the equivalent acceleration that would cause this deflection without a drop test. modeled the performance of a RF MEMS switch subjected to shock using a SDOF model. They simulated the performance of the switch to minimize the insertion loss. studied the combined effects of shock and electrostatics forces on MEMS devices both theoretically and experimentally. presented computationally efficient approaches to model microstructures and microbeams under mechanical shock. Other works are reviewed in Ref.

B.MEMS Response Under Shock Load (Including the Assembly Effect). remarked that the fundamental frequency of the package and the whole system
He concluded that shock test loading duration should be shorter than the period of lowest natural frequency of the system to avoid undesirable effect.

In this investigation, we assume that both the substrate-chip and the chip-PCB assembly are rigidly connected [2] the PCB directly as a single point force, the dynamic effect of the microstructure mass on the PCB is negligible, and the shock has a shape of a sine pulse of period c.

Suhir [26], Pitarresi and Primavera [24], Suhir and Burke [22], Bart et al. [18], and others have investigated the dynamic behavior of MEMS devices under shock and impact loads. Srikar and Senturia [2] explored the dynamic behavior of a liquid crystal display (LCD) to a shock load originated from a drop test. This LCD is packaged in a double box system (chassis and cabinet). They used a 2DOF lumped mass model and a continuous model to represent the system. To reduce the deflection of the LCD, they suggested designing the lower natural frequency of the system to be much less than the higher one. In this work, we show that following the above condition may lead to undesirable responses. Suhir [21] developed a mathematical model to evaluate the dynamic response of a microelectronic structure product/package to a drop and shock test. He concluded that shock test loading duration should be shorter than the period of lowest natural frequency of the system to avoid undesirable effect.

Suhir and Burke [22] studied the dynamic modeling of a PCB populated with electronic components under vibration load. Suhir [25] discussed the effect of viscous damping on the displacement and acceleration of an electronic equipment package under shock load. Suhir [26] determined the maximum acceleration experienced by electronic components mounted on a PCB under shock accounting for the nonlinear dynamic effects of the PCB. Wong [27] analyzed the dynamic behavior of a PCB under a drop impact. He used a lump mass, beam, and plate models to capture the dynamic behavior of the PCB. He concluded that the PCB response depends on the ratio between the frequency of the PCB and the input shock pulse. Keltie and Falter [28] presented guidelines that could be used to simplify the shock analysis of a rigid body mounted on a beam, which is common in electronic assembly. Wong et al. [29] studied the dynamics of a PCB assembly subjected to a half-sine shock load. To improve the assembly shock reliability they suggested to use a very thin or a very a thick PCB. The readers are referred to Refs. [21][30] for more information on shock on electronic equipment.

From the aforementioned review, we first note the lack of a comprehensive study on the effect of PCB motion on the MEMS response under shock load. Only qualitative guidelines to eliminate the undesirable effect of the PCB motion on the MEMS response have been presented so far [31][32]. It is noted that also, while there are some studies on the effect of the PCB motion on the response of electronic equipment, less attention has been given to the effect of the shock duration on their respective [21][31]. The main objective of the present study is to examine the effects of shock duration, damping, and electrostatic force on the response of a MEMS device based on a model that accounts for the PCB motion. Quantitative guidelines will be presented based on a case study, which could be used to element the PCB motion effect.

**D. Electrostatic MEMS Devices.** MEMS devices commonly involve capacitive sensing and/or actuation, in which one plate or electrode is actuated electrostatically and its motion is detected by capacitive change. There are numerous examples of MEMS devices, which depend on electrostatic excitation and detection, such as resonant microsensor, RF MEMS switches, and MEMS accelerometer devices. In this method, the driving load is the attractive force between two electrodes of a capacitor. The electrostatic load has an upper limit beyond which the mechanical restoring force of the microstructure can no longer resist its opposing electrostatic force, thereby leading to the collapse of the structure. This structural instability phenomenon is known as pull-in [32].

**Problem Formulation**

There are two approaches to model shock and impact on electronics devices. In one approach, a single point force is assumed to impact the PCB. Physically this could be due to a hammer hit. In the second approach the shock force is modeled as a pulse acceleration transmitted to the support of the structure, also called base excitation [33]. In this work, we consider the single impact force approach effects. The second approach will be investigated in Ref. [34].

In this investigation, we assume that both the substrate-chip and the chip-PCB assembly are rigidly connected [2][24]. Hence, the assembly effect reduces to that of the PCB motion only. We use a 2DOF model, Fig. 2, to study the assembly effect on the response of a MEMS device under shock load. The first DOF accounts for the PCB motion, which is subjected directly to the shock load. The second DOF represents the motion of the microstructure, such as a beam or a plate, which is mounted over the PCB.

Shown in Fig. 2 are the following: k_m microstructure stiffness; k_{PCB} PCB stiffness; c_m microstructure damping; c_{PCB} PCB damping; m_m microstructure mass; and m_{PCB} PCB mass. To evaluate the microstructure response under shock loads, it is assumed that the shock load is applied to the PCB directly as a single point force, the dynamic effect of the microstructure mass on the PCB is negligible, and the shock has a shape of a sine pulse of period T, Fig. 1, which represents a good representation for a shock pulse [35]. Under these assumptions, the governing equation of the undamped system is given by

\[
\begin{bmatrix}
m_m & 0 \\
0 & m_{PCB}
\end{bmatrix}
\begin{bmatrix}
x'' \\
x'
\end{bmatrix} + \begin{bmatrix}
k_m & -k_m \\
-k_m & k_{PCB}
\end{bmatrix}
\begin{bmatrix}
x \\
x'
\end{bmatrix} = F(t)
\] (1)
where $F(t)=0,F'_0\sin(\omega_{\text{pulse}} t)\sin(t\sin(\omega_{\text{pulse}} t))$ where $t$ is time, $u(t)$ is the unit step function, $\omega_{\text{pulse}}$ is the shock pulse frequency, and $tr$ denotes transpose. Using modal analysis, the responses of the microstructure and the PCB are given by

$$x_i = X_i\eta_i$$  \hspace{1cm} (2)

where $x_i$ is the microstructure response, $x_2$ is the PCB response, $X_i$ is the $i$th eigenvector, and

$$\eta_i = \frac{q_i\left[\left(\sin(\omega_{\text{pulse}} t) - \frac{\omega_{\text{pulse}}}{\omega_{n_i}} \sin(\omega_{n_i} t)\right)u(t)\right]}{m_i(\omega_{n_i}^2 - \omega_{n_i}^2)} \quad \text{for } t < T$$ \hspace{1cm} (3)

$$\eta_i = \frac{q_i\left[\left(\sin(\omega_{\text{pulse}} t) - \frac{\omega_{\text{pulse}}}{\omega_{n_i}} \sin(\omega_{n_i} t)\right)u(t)\right]}{m_i(\omega_{n_i}^2 - \omega_{n_i}^2)} + \frac{q_i\left[\left(\sin(\omega_{\text{pulse}}(t - T) - \frac{\omega_{\text{pulse}}}{\omega_{n_i}} \sin(\omega_{n_i}(t - T))\right)u(t - T)\right]}{m_i(\omega_{\text{pulse}}^2 - \omega_{n_i}^2)} \quad \text{for } t > T$$ \hspace{1cm} (4)

where $q_i\lambda^T F(t)$, $\omega_{n_i}$ is the modal natural frequency, and $m_i$ is the effective mass for each modal coordinate. In this system, the undamped coupled modal frequencies ($\omega_1$, $\omega_2$) have approximately the same values of the uncoupled natural frequencies of the microstructure and the PCB separately. Next, we assume proportional constant damping and solve for the light damped response of the microstructure and the PCB, which yields

$$x_i = X_i\eta_{di}$$ \hspace{1cm} (5)

where

$$\eta_{di} = \frac{q_i\lambda}{m_i\lambda^2(2 - \lambda^2 - 4\zeta^2) - \lambda^2 - 1} \left[\frac{\lambda^2 - 1}{\lambda} \sin(\omega_{\text{pulse}} t) + 2\xi(\cos(\omega_{\text{pulse}} t) - e^{-\zeta t}) \cos(\sqrt{1 - \zeta^2} \omega_i)}\right]$$

$$\frac{F(t)\lambda}{m_i\lambda^2(2 - \lambda^2 - 4\zeta^2) - \lambda^2 - 1} \left[\frac{e^{-\zeta t}}{\sqrt{1 - \zeta^2}} (1 - 2\zeta^2 - \lambda^2) \sin(\sqrt{1 - \zeta^2} \omega_i)\right] \quad \text{for } t < T$$ \hspace{1cm} (6)

$$\eta_{di} = \frac{q_i\lambda}{m_i\lambda^2(2 - \lambda^2 - 4\zeta^2) - \lambda^2 - 1} \left[\frac{\lambda^2 - 1}{\lambda} \sin(\omega_{\text{pulse}}(t - T)) + 2\xi(\cos(\omega_{\text{pulse}}(t - T)) - e^{-\zeta t}(t - T)) \cos(\sqrt{1 - \zeta^2} \omega_i)}\right] + \frac{q_i\lambda}{m_i\lambda^2(2 - \lambda^2 - 4\zeta^2) - \lambda^2 - 1} \left[\frac{e^{-\zeta(t - T)}}{\sqrt{1 - \zeta^2}} (1 - 2\zeta^2 - \lambda^2) \sin(\sqrt{1 - \zeta^2} \omega_i(t - T))\right] \quad \text{for } t > T$$ \hspace{1cm} (7)

where $\lambda=\omega_{\text{pulse}}/\omega_i$ and $\xi$ is the damping ratio [36].

### Results

In this investigation, we chose a MEMS omnidirectional pressure microphone employing a microdiaphragm [37] as a case study. This diaphragm has a fundamental natural frequency $\omega_{\text{MEMS}}=24$ kHz.

**A. Undamped Response.** First, we consider the undamped response of the diaphragm. This represents a worst-case scenario for the response of microstructures under shock. Figure 4(a) shows the response of the diaphragm $x_1$ to a shock acceleration pulse of a half-sine shape of duration $T=1.0$ ms using a 1DOF model of the diaphragm alone (without the PCB) [13]. The response is normalized to the static deflection of the diaphragm due to an equivalent static load $F_0/k_1$. It can be seen that the diaphragm responds quasistatically, since its natural period is much smaller than the duration of the shock. Next, we consider the effect of the PCB on the response. Figure 4(b) shows the normalized response of the diaphragm relative to that of the PCB $x_2$ using the 2DOF model. Here, the natural frequency of the PCB $\omega_{\text{PCB}}$ is chosen much less than the natural frequency of the microstructure $\omega_{\text{MEMS}}$. Here, the response of the diaphragm is amplified significantly.

To better understand the reason of this interesting behavior of the diaphragm, we investigate the effect of the fundamental natural frequency of the PCB and the shock pulse duration. Figure 5 shows the maximum normalized relative amplitude of the diaphragm for different $\omega_{\text{PCB}}$ values for shock duration ranging from 60 $\mu$s to 6.0 ms, which spans the practical experimental values [2]. Selected points in Figs. 5(b)5(c) were verified in Fig. 6 using ANSYS software [38]. The element COMPIN14 was used to model the springs and the structural mass element was used to model the masses. The $F$ command was used to apply a half-sine input force directly to the PCB. The two figures show good agreement between the 2DOF model and the ANSYS model.
Figure 5 indicates that the diaphragm response is amplified for specific zones of $\omega_p$, shown in shaded areas, where the normalized response exceeds unity. The width of these frequency bands depends strongly on the shock duration values. For the case of $T=6.0$ ms, there are two narrow zones corresponding to $\omega_p=0.0$ Hz–1.2 kHz and $\omega_p=23$ kHz–25 kHz. As $T$ decreases, the width of the two zones increases and they approach each other. Eventually, they merge into one zone, as depicted in Figs. 5(c)–5(d).

As noted from Fig. 5, there are three primary variables governing the behavior of the microstructure: $T$, $\omega_p$, and $\omega_{MEMS}$. To span completely the design space of a microstructure, a 3D plot needs to be generated accounting for these variables. Figure 7 depicts an example of such for the studied diaphragm. The figure shows the maximum normalized response of the diaphragm relative to that of the PCB for different $\omega_p$ and shock pulse frequency $\omega_{pulse}$ values. Here, only the magnitude of the displacement is shown, regardless of its sign. Figure 7(a) is for the case of $\omega_p/\omega_{MEMS}<1$ and Fig. 7(b) is for the case of $\omega_p/\omega_{MEMS}>1$. The diagram is split into two parts because the response is infinite (no damping) when the value of $\omega_p/\omega_{MEMS}$ is equal to 1.

In summary, Figs. 5–7 show that when the shock pulse duration is approximately larger than 0.1 ms, two small zones, where the diaphragm response is amplified, are defined. However, when the shock duration is approximately less than 0.1 ms, the two regions merge into one large region. Next we explore these two cases in more depth.

A1. Case 1. The diaphragm response in this region is amplified within two zones (Figs. 5(a)–5(b)). The first zone is defined when the PCB experiences the shock load as a dynamic load (its natural period is close to the shock duration). The second zone is defined when the fundamental natural frequency of the PCB coincides with that of the microstructure. The span of the two zones decreases as the shock duration increases.

A2. Case 2. In this region, the two zones in Case 1 are merged into one zone. The reason behind this merging is that the shock duration value is very small in this region. Hence, the frequency band at which the PCB amplifies the input shock is increased. To clarify this merging more, we show in Fig. 8 the maximum normalized amplitude of the PCB response for different $\omega_p$ values for shock durations of $T=1.0$ ms and $T=0.1$ ms. It is clear from the figures that as the shock duration value decreases the span at which the PCB response will be amplified is increased. Hence, this will widen the frequency band of the amplified response of the microstructure. Interestingly, for this case, the diaphragm response to a shock load might exceed significantly the equivalent static deflection of the same shock load (although we are away from the traditionally known as resonance condition, which occurs when $\omega_p=\omega_{MEMS}$). For example, Fig. 9 shows the time history for the normalized diaphragm response relative to the PCB when $T=60$ $\mu$s and $\omega_p=19.2$ kHz where its maximum value exceeds three times the corresponding static deflection of the diaphragm.

B. Damped Response. Next, we investigate the light damping effect on the response of the diaphragm under shock loads. Figure 10 shows a 3D plot representing the maximum relative normalized diaphragm response in the case of a damping ratio $\zeta=0.05$, for different $\omega_p$ and $\omega_{pulse}$. Figures 11(a)–11(b) show the maximum normalized relative amplitude of the diaphragm for different $\omega_p$ values for shock durations of 1.0 ms and 60 $\mu$s. The figures indicate that damping has a significant effect on the amplification zone that corresponds to the coincidence of the natural frequencies of the microstructure and the PCB, while it has much less effect on the zone where the PCB experiences the shock as a dynamic load.

The previous results (Figs. 4–5, 7–9, 10, 11) indicate that neglecting the motion effect of a PCB, which represents one of the MEMS packaging levels, Fig. 1, on the response of a microstructure during shock may lead to amplification of its response. This is contradictory to what has been mentioned in literature that the worst-case scenario for the effect of the package is to merely transfer the shock pulse to the microstructure without significantly altering its shape or intensity [3]. Further, Figs. 5, 11 show that designing the package or the PCB to have a much lower natural frequency than the microstructure, while attempting to separate the frequency of the microstructure from the PCB, may also result in amplification for the shock force affecting it.

C. Comparison Between a Continuous-Lumped Model With the 2DOF Model of a Clamped-Clamped Beam. In a previous work [19] we developed a continuous model of a clamped-clamped microbeam that is coupled with a lumped mass model of the PCB. Here we compare the results obtained of the 2DOF model with the model of Ref. [19]. To this end, the effective stiffness of the clamped-clamped beam is obtained according to the following equation:

$$k = \frac{32EbI^3}{f^3}$$

(8)

Figures 12, 13 compare the results of the model in Ref. [19] with the 2DOF model results when the shock duration values are 1.0 ms and 0.1 ms, respectively. The figures show that the results are in good agreement. It is worth to mention here that in these figures, the effects of geometric nonlinearity of the continuous-lumped model has been neglected to enable comparison with the 2DOF model. This puts some limitation on the use of the 2DOF model to represent clamped-clamped beams and other structure suffering nonlinear behaviors. Also other limitations of the 2DOF include neglecting the fact that the PCB is a flexible structure that has an infinite number of modes of vibrations. These modes of vibration are expected to have an effect on the microstructure response if their natural period values are within the shock duration value. However, a clear advantage of the 2DOF model is its flexibility and ability to describe many microstructures, not only beams, which can be of irregular shapes.
Effect of Electrostatic Forces

Here, we study the combined effect of assembly and electrostatic force on the response of the diaphragm to shock loads. In this investigation, we use a SIMULINK model [39] to tackle the nonlinear electrostatic force and integrate the equations of motions numerically with time. Here the system is governed by Eq. (1); however, the forcing term becomes

\[
F(t) = \left[ \frac{\varepsilon A V_\text{dc}^2}{2(d-x_r)^2} F_0 [\sin(\omega_{\text{puls}} t) u(t) + \sin \omega_{\text{puls}} (t-T) u(t-T)] \right]
\]  

(9)

where \(x_r\) is the relative deflection of the diaphragm, \(V\) is the dc polarization voltage, \(A\) is the area of the diaphragm cross section, \(d\) is the capacitor gap width between the diaphragm and the stationary electrode on the PCB, and \(\varepsilon\) is the dielectric constant of the gap medium. The diaphragm has \(A=1\times1\text{ mm}^2\). In the following analysis we assume complete overlapping between the two electrodes of the diaphragm.

Figure 14(a) shows the relative normalized response of the diaphragm to a shock pulse acceleration of amplitude 1000 g and \(T=0.25\text{ ms}\). We assume a voltage load \(V_\text{dc}=31\text{ V}\) and a PCB fundamental natural frequency 28.8 kHz. The figure indicates that the diaphragm has a stable response. On the other hand, Fig. 14(b) shows the diaphragm response to the same shock pulse but with a voltage value of 27 V and \(\omega_{\text{puls}}=1.92\) kHz. Although in the latter case the electrostatic force is less than the first case, the diaphragm exhibit pull-in (unstable response). This can be justified by the fact that, according to Figs. 5,7, the small natural frequency of the PCB amplifies the shock loads on the diaphragm.

Figure 14.

Figure 15 compares the pull-in voltage for the diaphragm against the shock amplitude of a half-sine pulse when modeling the diaphragm alone (without the PCB) (dashed) and with the PCB effect included (solid). We assume \(T=0.25\text{ ms}\) and \(\omega_{\text{puls}}=2.64\) kHz. Here, also it is noted that the 2DOF model shows an earlier pull-in compared to the 1DOF model. The above results indicate the importance of modeling the effect of the PCB motion on electrostatic MEMS. By neglecting the effect of the PCB, there is a possibility that the device will fail to function properly and it might collapse and fail mechanically.

Figure 15.

Summary and Conclusions

We investigated the response of MEMS devices under shock loads including the effect of the PCB motion. We used a 2DOF model for this investigation. A pressure microphone employing a microdiaphragm was chosen as the case study. We studied the effects of the fundamental natural frequency of the PCB, electrostatic force, damping, shock pulse duration, and their interactions. It was found that neglecting the PCB effect on the modeling of MEMS under shock loads can lead to erroneous predictions of the microstructure motion, especially for two cases: when the PCB experiences the shock load as a dynamic load and when the natural frequency of the PCB approaches that of the microstructure. The response is also found to depend strongly on the shock duration values.

Contradictory to what is mentioned in literature that a package, as a worst-case scenario, transfers the shock pulse to the microstructure without significantly altering its shape or intensity, we showed that a poor design of the package (PCB) might result in severe amplification of the shock effect. This amplification can cause early pull-in instability for MEMS devices employing electrostatic forces.

Future Work

As a future plan, more work is needed to verify experimentally the impact shock load effects. An experimental setup consisting of a hammer, an accelerometer, different PCB designs, and a differential laser vibrometer that has the ability to read two different measurement points at the same time can be used for this purpose. The hammer will be used to hit the PCB to simulate an impact shock load, and the differential laser will be used to read the MEMS and the PCB responses simultaneously. However, since controlling the hammer impact and using two laser readout systems might be difficult, it might be easier to design a base-excitation shock load using a well controllable shaker. This excitation method is found to share many similarities with the single point force assumed in this study. The theoretical and experimental work due to base excitation shock will appear in Ref. [34]. As an example, Fig. 16 shows one of the obtained results for a real MEMS device response with and without the PCB under base shock excitation [34].

Figure 16.

Acknowledgment

This work has been supported by NSF Award No. 0700683.

REFERENCES

http://scitation.aip.org/journals/doc/JEPAE4-ft/vol_130/iss_3/031002_1.html 10/21/2008
An Investigation Into the Effect of the PCB Motion on the Dynamic Response of MEMS...

FIGURES

1. Schematic of the assembly (packaging) levels of a MEMS device

2. A 2D model of a microstructure mounted on a PCB
Fig. 3 Schematic of a half-sine pulse used to model actual shock loads First citation in article

Fig. 4 Time history for the normalized displacement of the diaphragm for a half-sine pulse of $T=1.0$ ms First citation in article

Fig. 5 The maximum normalized relative amplitude of the diaphragm for different $\omega_p$ values. The results are shown for a half-sine pulse for the case of no damping. First citation in article

Fig. 6 A comparison of the microstructure response to impact shock load using ANSYS and the modal analysis solution First citation in article

Fig. 7 The maximum normalized relative amplitude of the diaphragm for different $\omega_p$ and $\omega_{\text{pulse}}$ values First citation in article

Fig. 8 The maximum normalized amplitude of the PCB response for different $\omega_p$ values First citation in article

Fig. 9 Time history for the normalized relative displacement of the diaphragm when $\omega_p=19.2$ kHz and $T=60$ $\mu$s First citation in article

Fig. 10 The maximum normalized relative amplitude of the diaphragm for different $\omega_p$ and $\omega_{\text{pulse}}$ values when $\zeta=0.05$ First citation in article

Fig. 11 The maximum normalized relative amplitude of the diaphragm for different $\omega_p$ values when $\zeta=0.05$ First citation in article

Fig. 12 The response of the MEMS-PCB assembly to an impact shock load of shock duration $T=1$ ms: (a) response spectrum and (b) transit response for the continuous-
Fig. 13 The response of the MEMS-PCB assembly to an impact shock load of shock duration $T=0.1$ ms: (a) response spectrum and (b) transient response for the continuous-lumped model [19] First citation in article

Fig. 14 Time history for the normalized relative response of the diaphragm to a half-sine pulse of $T=0.25$ ms, showing (a) a stable response when $f_p=28.8$ kHz and $V_{dc}=31$ V, and (b) a pull-in state (unstable response) when $f_p=1.92$ kHz and $V_{dc}=27$ V First citation in article

Fig. 15 A plot of the pull-in voltage of the diaphragm against shock load amplitude of a half-sine pulse, accounting for the PCB motion (solid) and neglecting the PCB motion (dashed). The results are shown for the case $T=0.25$ ms and $f_p=2.64$ kHz. First citation in article

Fig. 16 The transient response of a capacitive MEMS device with and without a PCB when subjected to base shock load generated by a controllable shaker, as monitored through a laser doppler vibrometer ($T=5.0$ ms, and the ratio between the natural frequency of the PCB to the MEMS is 1.24) [34] First citation in article