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The Effect of Corrugations on Mechanical Sensitivity of Diaphragm for MEMS Capacitive Microphone

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ABSTRACT

In this paper the effect of corrugations on mechanical sensitivity of diaphragm for MEMS capacitive microphone is investigated. Analytical analyses have been carried out to derive mathematic expression for mechanical sensitivity and displacement of corrugated diaphragm with residual stress. It is shown that the mechanical sensitivity and displacement of diaphragm can be modeled using thin plate theory. The mechanical stress of corrugated diaphragm is calculated using mathematical model and its relationship with residual stress is expressed. The analytical results show that the mechanical sensitivity of diaphragm can be increased using corrugations, because of reducing the effect of residual stress in corrugated diaphragm.

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1. INTRODUCTION

Microphone is a transducer that converts acoustic energy to electrical energy. It is widely used in voice communications, hearing aids, noise and vibration control and biomedical application [1-3]. During the past years, the capacitive microphone has been the most attractive research topic in micro-electromechanical systems (MEMS), because it has superior characteristics such as high sensitivity and low noise level compared with piezoelectric and piezoresistive microphones [4, 5]. Till now, most of MEMS capacitive microphones were developed using flat diaphragm to sense acoustic wave, because it is easy to fabricate [6].

The capacitive microphones generally consist of a diaphragm which vibrates by impinging of acoustic wave pressure, a back plate and air gap. In its simplest form, a flat diaphragm is stretched over a conductive back plate and supported by post so that there is a gap between the diaphragm and the back plate. The high residual stress diaphragm may give undesirable effects such as higher actuation voltage, film buckling and diaphragm cracking. The mechanical sensitivity of diaphragm is limited by residual stress of deposited layer. The residual stress can be controlled by the parameters of the deposition process [7].

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Since the control of thin film stress during the fabrication process is rather difficult, therefore making shallow corrugations in diaphragm can reduce the effect of residual stress and subsequently increase the mechanical sensitivity of diaphragm. In this paper, we investigate the effect of corrugations on mechanical sensitivity and diaphragm deflection for using it for the first time in MEMS capacitive microphone.

2. MODELING OF MECHANICAL SENSITIVITY

The center deflection (y) of a flat circular diaphragm with clamped edges and without residual stress, due to a homogeneous pressure (P) can be calculated from [8]:

$$\frac{PR^4}{Eh^4}=\frac{5.33}{1-v^2}\left(\frac{y}{h}\right)+\frac{2.83}{1-v^2}\left(\frac{y}{h}\right)^3 \tag{1}$$

where E, v, R and h are Young's modulus, Poisson's ratio, radius and thickness of diaphragm, respectively. It is illustrated from Equation (1) that if $(y/h)<<1$ the cubic term of displacement can be neglected, thus the relation between center deflection and applied pressure is linear. For large values of (y/h) the relation is nonlinear. For large value of initial tension, the deflection of a flat circular diaphragm can be represented by [8]:

$$\frac{PR^4}{Eh^4} = \frac{4\sigma_0 R^2}{Eh^2}\left(\frac{y}{h}\right) \tag{2}$$

where σ_0 is residual stress. Using the principle of superposition, resistance to bending due to residual stress can be added to Equation (1). So the center deflection can be calculated from:

$$\frac{PR^4}{Eh^4} = \left(\frac{5.33}{1-v^2} + \frac{4\sigma_0 R^2}{Eh^2}\right)\frac{y}{h} + \frac{2.83}{1-v^2}\left(\frac{y}{h}\right)^3 \tag{3}$$

For small deflection, the mechanical sensitivity of a flat circular diaphragm ($S_m = dy/dP$), by neglecting the 3rd order term, can be expressed as:

$$S_m = \frac{R^2}{4h\left[\sigma_0 + \frac{4Eh^2}{3(1-v^2)R^2}\right]} \tag{4}$$

According to Equation (4), the mechanical sensitivity of a circular diaphragm is approximately inversely proportional to its residual stress. The residual stress of diaphragm depends on fabrication process. It can be controlled within certain limits by the parameters of the deposition process. Since accurate control of thin film stress during the fabrication process is rather difficult, therefore by making shallow corrugations in diaphragm the effect of residual stress can be reduced and subsequently the mechanical sensitivity of diaphragm increases. The corrugated diaphragm with residual stress, σ_0, acts similar to planar diaphragm with a reduced stress, σ. It means that the stress of a corrugated diaphragm can be written as:

$$\sigma = \eta\sigma_0 \quad \eta < 1 \tag{5}$$

where σ is equilibrium stress of corrugation diaphragm, σ_0 is residual stress and η is attenuation coefficient of stress. By introduction of corrugations in diaphragm structure, the center deflection of a corrugated circular diaphragm with clamped edges and without stress can be expressed as [9]:

$$P = a_p E \frac{h^4}{R^4}.\frac{y}{h} + b_p \frac{E}{(1-v^2)}.\frac{h^4}{R^4}.\frac{y^3}{h^3} \tag{6}$$

where a_p is the dimensionless linear coefficient and b_p is the dimensionless non-linear coefficient [9].

$$a_p = \frac{2(q+1)(q+3)}{3\left(1+\frac{v^2}{q^2}\right)} \tag{7}$$

$$b_p = 32\frac{1-v^2}{q^2-9}\left(\frac{1}{6} + \frac{3-v}{(q-v)(q+3)}\right) \tag{8}$$

where q is corrugated profile factor which is given by the following equations [9]:

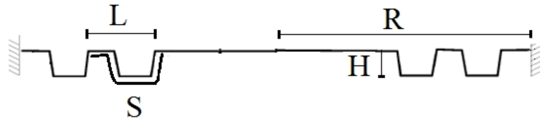

Figure 1. Cross section of corrugated diaphragm

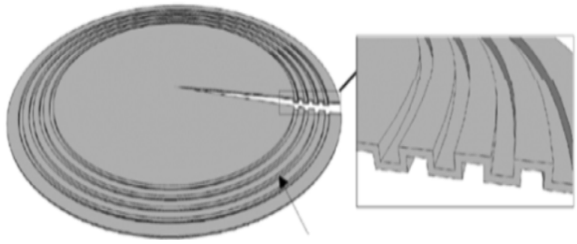
Figure 2. Corrugated diaphragm


Figure 3. Cross section of corrugated diaphragm

$$q^2 = \frac{S}{L}\left(1+1.5\frac{H^2}{h^2}\right) \tag{9}$$

where S, L, H and h are the spatial period, arc length, depth of corrugations and diaphragm thickness, respectively (see Figure 1). For large values of initial tension the deflection of a corrugated circular diaphragm can be represented by:

$$\frac{PR^4}{Eh^4} = \frac{4\sigma R^2}{Eh^2}\left(\frac{y}{h}\right) \tag{10}$$

where σ is equilibrium stress of corrugated diaphragm. Using the principle of superposition, the center deflection of a circular corrugated diaphragm with clamped edges can be calculated from:

$$P = \left[a_p E \frac{h^4}{R^4} + \frac{4h^2\sigma}{R^2}\right]\frac{y}{h} + b_p \frac{E}{(1-v^2)}.\frac{h^4}{R^4}.\frac{y^3}{h^3} \tag{11}$$

According to Equation (5), to obtain stress, σ, in corrugated diaphragm, η should be calculated. To obtain η, we consider circular corrugated diaphragm with trapezoidal wave (see Figuer 2). Figure 3 shows the geometric model of a corrugated structure that consists of flat and corrugated zone.

To investigate the effect of the corrugations, first the effect of one wave is considered, and then by multiplying it with wave's number the general Equation is obtained. Figure 4 shows one wave which is stretched by the force, F. This force causes two types of length increase. The first type is due to the elasticity of the

material that makes change in element length in direction of force. Another one is due to vertical force to the object which makes a bending moment that causes angle changes. These changes cause element length to change to its primary mode. For simplification, we consider half of a corrugation. Where w_c, h_c and b_c are width, height and space between waves. Total changes over the unit cell can be attributed according to Figure 5 into three parts *A*, *B* and *C*. In part *C* there is not vertical force, thus the moment can not be created and the length change is due to the tensile force.
Length change in part of *C* is [10]:

$$\Delta L_1 = \int_0^{b_c/2} \frac{F}{AE}.dx = \frac{F.b_c}{2.AE} \tag{12}$$

where *A* is the area of the force exertion, and *E* is Young's modulus. According to Figure 6, both vertical and parallel surface forces exist in part of B, thus they create two types of length changes.

The height of the corrugation is small, so the stretching of h_c is negligible. But the force ($F.\sin\beta$) causes bending in the arm. The bending and increasing length have been illustrated in Figure 7.

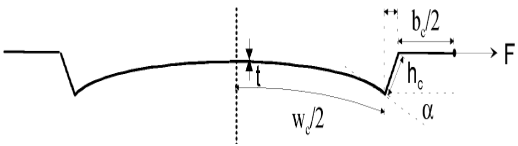

Figure 4. One of corrugation under force F

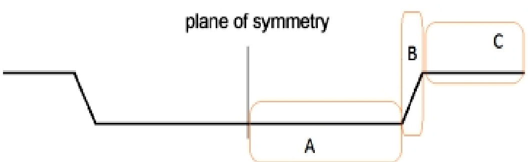

Figure 5. Wave of diaphragm

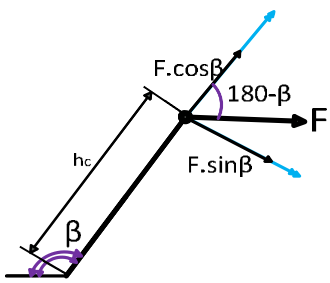

Figure 6. Force analysis of the arm

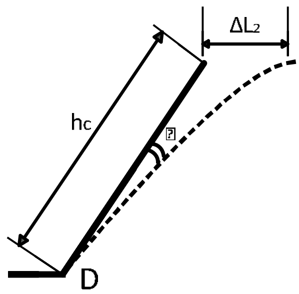

Figure 7. Length changes due to bending

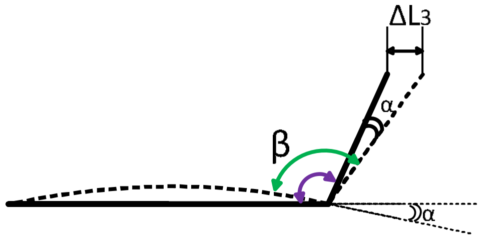

Figure 8. Length changes by bending part of A

The arm's bending moment formula can be written as [10]:

$$M_{(x)} = X.F.\sin\beta \tag{13}$$

X is the length of element under bending moment. Using Castiglione's theorem, length change can be calculated from [10]:

$$\Delta L_2 = \int_0^{h_c} \frac{M_{(x)}}{E.I}.\frac{\partial M_{(x)}}{\partial F}.dx = \frac{F.h_c^3.\sin^2\beta}{3.E.I} \tag{14}$$

I is the moment of inertia and defined as [10]:

$$I = \frac{b.t^3}{12} \tag{15}$$

where *b* is the length of the area that force, *F*, inters to it and *t* is diaphragm thickness. Therefore, the total displacement of ΔL_2 is given by:

$$\Delta L_2 = \frac{4.F.h_c^3.\sin^2\beta}{E.b.t^3} \tag{16}$$

In part of A, both vertical and parallel surface forces exist. So they create two types of length changes. First, we study bending over A as illustrate in Figure 8. Maximum moment entered at point D and moment in part of A can be achieved with linear distribution of the maximum moment along length of A and defined as follow:

$$M_{(x)} = \frac{2.h_c}{w_c}.X.F.\sin\beta \tag{17}$$

According to Castiglione's theorem the angle, α, is equal to [10]:

$$\alpha = \int_0^{w_c/2} \frac{M_{(x)}}{E.I}.dx = \frac{3.F.h_c.w_c.\sin\beta}{E.b.t^3} \tag{18}$$

and by considering α <<1:

$$\Delta L_3 = \alpha.h_c = \frac{3.F.h_c^2.w_c.\sin\beta}{E.b.t^3} \tag{19}$$

Length change to tensile force is:

$$\Delta L_4 = \int_0^{w_c/2} \frac{F}{AE}.dx = \frac{F.w_c}{2.AE} \tag{20}$$

In addition, temperature change can also change the strain as expressed below:

$$\varepsilon = \frac{\sigma_0}{E} = \gamma.\Delta T \tag{21}$$

where ε , γ and T are the strain, coefficient of thermal expansion and temperature, respectively. From Equation (21) we have:

$$\sigma_0 = \gamma.\Delta T.E \tag{22}$$

Under thermal stress, the sum of elastic and thermal displacements of the corrugated and planar region should be zero:

$$\Delta X_a^t + \Delta X_a^e + \Delta X_c^t + \Delta X_c^e = 0 \tag{23}$$

where ΔX_c^e, ΔX_c^t, ΔX_a^e and ΔX_a^t are corrugations elastic displacement, corrugations thermal displacement, flat elastic displacement and flat thermal displacement respectively, that can be calculated from following equations:

$$\Delta X_c^e = \Delta L_1 + \Delta L_2 + \Delta L_3 + \Delta L_4 \tag{24}$$

$$\Delta X_c^t \approx \gamma.\Delta T.N_c.(w_c + b_c) \tag{25}$$

$$\Delta X_a^e \approx \frac{F.(R - N_c(w_c + b_c))}{AE} \tag{26}$$

$$\Delta X_a^t \approx \gamma.\Delta T(R - N_c.(w_c + b_c)) \tag{27}$$

Rewriting Equation (23) as following:

$$\frac{F.R}{AE} + \gamma.\Delta T.R + \frac{8.F.h_c^3.\sin^2\beta}{E.b.t^2} + \frac{6.F.h_c^2.w_c.\sin\beta}{E.b.t^2} = 0 \tag{28}$$

The equilibrium stress, σ , in a corrugated diaphragm as a function of the residual stress, σ_0 is given by:

$$\eta = \frac{\sigma}{\sigma_0} = \frac{R.t^2}{R.t^2 + 6N_c.h_c^2.w_c.\sin\beta + 8N_c.h_c^3.w_c.\sin^2\beta} \tag{29}$$

where:

$$\sigma = -\frac{F}{b.t} \tag{30}$$

For shallow trapezoidal corrugations, the central deflection of a circular corrugated diaphragm with clamped edges and residual stress can be calculated as:

$$P = [a_p E\frac{h^4}{R^4} + \frac{4h^2\eta\sigma_0}{R^2}]\frac{y}{h} + b_p\frac{E}{(1-\nu^2)}.\frac{h^4}{R^4}.\frac{y^3}{h^3} \tag{31}$$

For small deflections, the mechanical sensitivity of a corrugated circular diaphragm (S_m = dy/dp) can be calculated as:

$$S_m = \frac{R^2}{h[4\eta.\sigma_0 + E.ap.\frac{h^2}{R^2}]} \tag{32}$$

3. RESULT AND DISCUSSION

In this section, we present mechanical sensitivity and central deflection of corrugated diaphragm and compare it with flat diaphragm. The mathematical analysis using MATLAB has been done to predict the diaphragm performance. In this work, a flat diaphragm and a corrugated diaphragm with Poisson's ratio of 0.22, Young's modulus of 160 GPa, diaphragm radius of 0.5 mm, diaphragm thickness of 2μm and for corrugated diaphragm, $h_c = 3um$, $N_c = 5$, $W_c = 10\,um$, $b_c = 7\,um$, $\beta = 90°$ have been assumed. Figure 9 shows pressure-deflection curves of a flat and corrugated circular diaphragm without residual stress.

If only small deflections are considered, it can be seen that the corrugated diaphragm is stiffer than a flat diaphragm caused by the larger flexural rigidity in the tangential direction. On the other hand, the linear area of the load-deflection curve for the corrugated diaphragm is increased. In larger deflection ranges, the corrugated diaphragm has lower stiffness than the flat diaphragm. The above descriptions are true if the residual stress of diaphragm is zero. As well known, because of fabrication process in MEMS diaphragm, the residual stress cannot be zero.

Figure 10 shows the central deflection of corrugated diaphragm versus pursuer with residual stress of 100MPa. It can be seen that, in small and large displacement, flat diaphragm is stiffer than corrugated diaphragm.

Behavior of a corrugated diaphragm is determined by the number of corrugations (N). It is easy to find that the corrugation numbers are the most effective parameter to influence the behavior of corrugated diaphragms. Figure 11 shows the central deflection of circular corrugated diaphragms versus pressure for different number of corrugations. In this example, the residual stress is 200 MPa. Figure 11 shows the effect of corrugation numbers on performance of a circular corrugated diaphragm. As the number of corrugations increases, the central deflection also increases under same load.

Residual stress is an important factor in the modeling and simulation of diaphragms. Figure 12 shows the effect of residual stress on performance of a circular corrugated and a flat diaphragm. As the residual stress increases, the diaphragm center deflection decreases under the same load. However at small pressures the effect of residual stress is quite small, at larger pressures it becomes much larger. It is shown that the effect of residual stress on the deflection of corrugated diaphragms is much smaller than flat diaphragms.

It can be seen clearly that a flat diaphragm is more rigid than a corrugated diaphragm at both small and large deflections when both diaphragms have same residual stress. The effect of residual stress can be decreased in diaphragm using corrugations. Mechanical sensitivity is an important parameter in MEMS acoustic sensor.

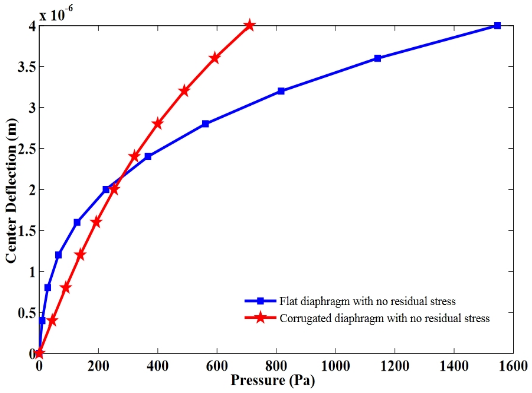

Figure 9. Central deflection of corrugated and flat diaphragm

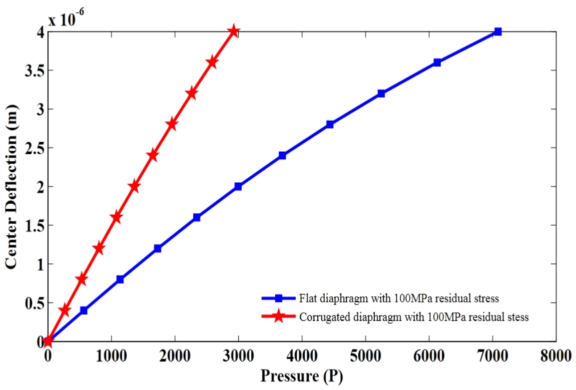

Figure 10. Central deflection of corrugated and flat diaphragm with residual stress

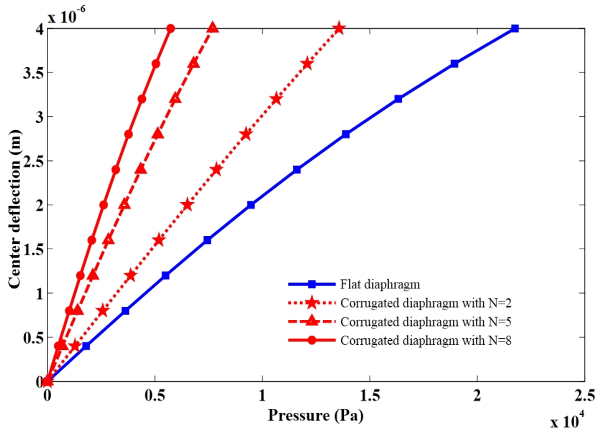

Figure 11. Central deflection of corrugated and flat diaphragm with N=2, 5, 8

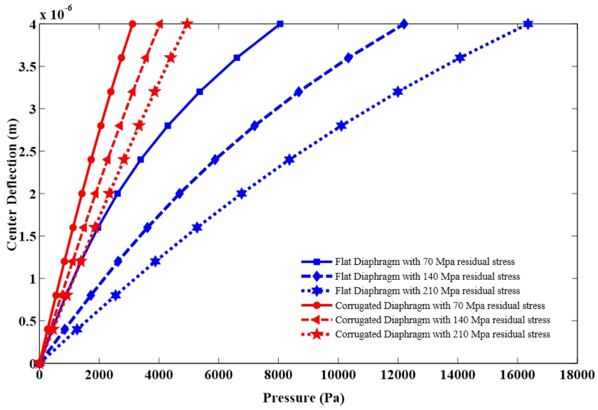

Figure 12. Central deflection of flat and corrugated diaphragm with residual stress of 70MPa, 140 MPa, 210MPa

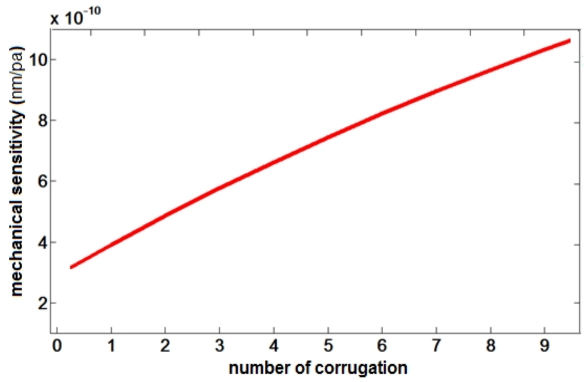

Figure 13. Mechanical sensitivity of corrugated diaphragm with residual stress of $\sigma_0 = 100MPa$

Figure 13 shows the calculated mechanical sensitivity of the corrugated diaphragms with different corrugation numbers. It can be seen that by increasing the corrugation numbers the mechanical sensitivity increases.

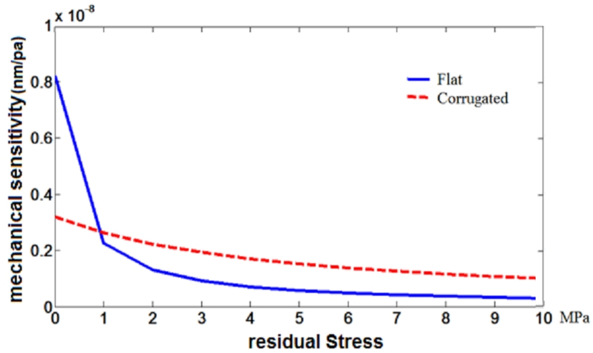

Figure 14. Mechanical sensitivity of corrugated diaphragm with residual stress of $\sigma_0 = 100MPa$

In Figure 14, the mechanical sensitivity of flat diaphragms versus residual stress is compared with corrugated circular diaphragms. In low stress (less than 1 Mpa), the flat diaphragm has higher mechanical sensitivity than the corrugated one. In high stress (more than 1 Mpa), the corrugated diaphragm has higher mechanical sensitivity than the flat one. It can be seen that mechanical sensitivity of flat diaphragm is dependent on residual stress extremely but the effect of residual stress has been decreased in corrugated diaphragm. Most of thin films have more than 1 MPa residual stress, therefore it is better to use corrugated diaphragms.

4. COUNCUSION

The MEMS acoustic sensor can use the corrugated diaphragm to reduce the effect of residual stress in diaphragm. Analytical analyses have been presented to calculate the mechanical sensitivity and central deflection of circular corrugated diaphragm for MEMS acoustic sensor. The results show that the mechanical sensitivity and central deflection of corrugated diaphragm have little dependence on residual stress and strongly depend on the number and height of the corrugations. Thus by increasing the number or height of corrugations, the mechanical sensitivity and central deflection of diaphragm can be increased.

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The Effect of Corrugations on Mechanical Sensitivity of Diaphragm for MEMS Capacitive Microphone

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چکیده

در این مقاله به بررسی اثر موج‌ها بر روی حساسیت مکانیکی دیافراگم میکروفن‌های خازنی ساخته شده با ماشین کاری میکرونی می‌پردازیم. به منظور دستیابی به یک مدل ریاضی برای حساسیت مکانیکی و جابجایی دیافراگم موجدار با توجه به تنش پسماند، دیافراگم را مورد تجزیه و تحلیل قرار دادیم. در این مقاله نشان دادیم که حساسیت مکانیکی و جابجایی دیافراگم را می‌توان با استفاده از تئوری صفحات نازک مدل کرد. در ادامه تنش مکانیکی دیافراگم و رابطه آن با تنش پسماند با استفاده از مدل ریاضی محاسبه شده است. نتایج تحلیلی نشان می دهند که حساسیت دیافراگم با استفاده از موج‌ها بیشتر می شود که این موضوع به دلیل کاهش تنش پسماند در دیافراگم‌های موجدار است.

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