Modal and Vibration Analysis of Functionally Graded Dental Implant

Saeed Asiri¹*

¹Skills for Development and Consultation, Mechanical Engineering Department, Engineering College, King Abdulaziz University, P.O.Box 80204 Jeddah 21589, Saudi Arabia.

Author’s contribution
The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

Dental implant is considered to be the best treatment when dealing with the loss of teeth. It gives beautiful results and can last longer than most of other treatments. Since the Osseo-integration period is a critical period for implant stability, so the used material for dental implant is one of the most factors affecting the stability and Functionally Graded Material (FGM) is one of the opportunities to improve it. The aim of this research is to carry out modal analysis and vibration analysis analytically for functionally graded Dental Implant. In this study several models for dental implant was analyzed by ANSYS15.0 APDL. The functionally graded material was considered in three models. The same materials, Ti-HA, where used in all of them but with different ratio in each. The natural frequency and mode shapes were extracted for all models. The frequency responses of functionally graded Dental Implant after performing a static analysis for each modal have been studied. It was noticed using modal analysis that all of the extracted results for FGM are vary between the two basic materials and it is affected by the concentration of each. It is firmly believed that FGM is the future of dental implant due to the ability of designing a specific material property to be more stable. A comparison of the materials that utilized in FGM when the ration of each 100% was performed as well as an evaluation for the classical dental implant. It is firmly believed that FGM is the future of dental implant due to the ability of designing a specific material property to be more stable.

*Corresponding author: E-mail: asiri.net@gmail.com;
1. INTRODUCTION

Dental implant is considered the best treatment when dealing with the loss of teeth. The two main materials are used in implant fabrication are metal and ceramic. The metal implant is commonly used which is made of Titanium or Stainless Steel. The alloy of such materials are still considered and classified under metallic dental implant. The Titanium is used due to its physical prosperity such as the stiffness which near the bone stiffness. On the other hand, ceramic types are used in the last 15 years which is considered recent when compare with metallic implant. It can be fully integrated with living bones and this is very important factor to insure Osseo-integration to have the stability. One of the major areas to be studied for dental implant stability is the material type. The Titanium is used in dental implant because it has the ability of corrosion resistance and can be bonded with the living tissues. One of the big challenges today is to select the proper materials for dental implants to avoid the conflict between mechanical properties of engineered and natural biomaterials. This conflict usually produces bone remodeling problems. Functionally graded materials have been proposed as an upgrade that can reduce lot of these problems. Functionally graded material, FGM are materials that have their properties to change gradually over the volume changing from 100% of one component to grasp 50% of each component in the middle to finally reach 100% of the other component in the other side as shown in Fig. 1. It can be designed to modify the response of the material to meet up the design criteria. The FGM which contains ceramic on the outer surface and metal on the inner surface eliminates the rapid change between coefficients of thermal expansion, offers thermal protection, and provides load carrying capability. This is due to the material constituents of an FGM changes slowly through the thickness and therefore the stress concentrations from sudden changes in material properties are eliminated.

Many studies showed that functionally graded material for dental implant is a better and more suitable to be used comparing with the plain metal or ceramic material. A comparison study will be performed to analyze these studies. FGMs provide the structure with which synthetic biomaterials should essentially be formed. The size of material components is relatively small. In the case of dental applications, the components

\[ \text{Fig. 1. Illustration of Functionally Graded Material (FGM)} \]
if the material gradient parameter (n) in FGM dental implants on stress distribution to show that thread dimensions of functionally graded [6]. M. Kaman and N. Celik [7] studied the effects of stress and strain than homogenous materials using FGM material is enhancing the distribution results. It was concluded from this study that oblique loading condition and compares the load types used are horizontal, vertical, and amount of Ti and HA to the dental implant. Other two models have varied the implant.  Four models were developed and 3-D biomechanical behavior of FGM in dental Kasim, et al. [6] have studied and compared the implant materials with focus in Titanium implant and provided a literature review for dental R. Osman and M. Swain [5] have reviewed recently the dental implant materials with keeping the thread width constants. They use a technique to assigned material properties across the element by applying a spatial continuous variation in ration of each 100%. As well as an evaluation for the classical dental implant.

The idea of Functionally Graded Material FGM used in 1984 in Japan for a space project in which the combination of material is used to withstand the temperature of 2000 Kelvin and a temperature gradient of 1000 k across a 10 mm section [2]. The biomaterials used in dental implants need to many properties such as biocompatibility, strength, fatigue durability, nontoxic, corrosion resistance, and sometimes aesthetics [3]. H. Hedia and N. Mahmoud [4] have investigated and studied the effects of material type used in dental implant to come up with an optimum material to minimize the stresses in the implant and the bone to increase the implant life. R. Osman and M. Swain [5] have reviewed recently the dental implant materials and provided a literature review for dental implant materials with focus in Titanium implant and recent introduce martials. It was confirmed that the Titanium is still considered the main standard for producing the dental implant where the Zirconia implant is promising in the future with a need for more studies specially to minimize the mechanical failures [5]. N. Abu Kasim, et al. [6] have studied and compared the biomechanical behavior of FGM in dental implant. Four models were developed and 3-D finite elements analysis was accomplished. Two models used titanium with FGM made of Zircon and Alumina as first layer. These two models were compared with a homogenous Zirconia implant. Other two models have varied the amount of Ti and HA to the dental implant. The load types used are horizontal, vertical, and oblique loading condition and compares the results. It was concluded from this study that using FGM material is enhancing the distribution of stress and strain than homogenous materials [6]. M. Kaman and N. Celik [7] studied the effects of thread dimensions of functionally graded dental implants on stress distribution to show that if the material gradient parameter (n) in FGM increases, the equivalent stress decreases. A 2-D finite element model using ANSYS was used to overcome the investigation numerically. It was found that the minimum stress distribution increases when increasing the gradient factor “n”. It was also, resulted maximum von Mises stress increases when decreasing the length of the implant with keeping the thread width constants. They use a technique to assigned material properties across the element by applying a spatial continuous variation in assigned nodal temperature [7]. The implant resonance frequency (RF) and modal analysis were studied numerically and experimentally by R. Harirforoush [8] to investigate the effect of soft tissue on RF of implant. João Andrade [9] studied the relationship between the strain results on the mandible when a load is applied on a dental prosthesis and implants.

2. MATERIALS AND METHODS

In this study a finite element model using ANSYS 15 Mechanical APDL will be utilized for modeling dental implant shown in Fig. 3 and then to simulate the solution numerically. A typical ANSYS analysis process map shown in Fig. 4 will be followed.

ANSYS models will be generated and the result will be compared based on the implant materials. The material property for the cortical bone will remain constant (unchanged). On the other hand, the property of implant will be varying for each model. Table 1 shows the materials mechanical properties of the models.

Since many studies have confirmed that Ti-HA is considered optimal when compared with classical used materials, so in this study Titanium and Hydroxyapatite, Ti-HA, have been used for the implant model as functionally graded material as well as separate models. Zirconium Oxide seems to be a suitable implant material because of its tooth like color, mechanical properties, biocompatibility, and low plaque affinity. So, it is considered in this report as classic dental implant material.

The functionally graded material mechanical properties have been calculated using Excel program. This is to identify Young’s modulus of Elasticity (E), and Poisson ratio (\(\nu\)) at a certain height. The below equations were used by Hedia and Nemat-Alla to identify the required value.

\[
\nu = \left(\frac{E}{2}\right) \frac{m}{n} (1)
\]
\[ V_m = 1 - V_c \]  \hspace{1cm} (2)

\[ E_0 = E_c \left[ \frac{E_c + (G_m - E_c)V_m}{E_c + (G_m - E_c)(V_m^2 - V_m^2)} \right] \]  \hspace{1cm} (3)

\[ \vartheta = \vartheta_m V_m + \vartheta_c V_c \]  \hspace{1cm} (4)

Where:

- \( V_c \) volume fraction for ceramic
- \( V_m \) volume fraction for metal
- \( h \) total height for the implant
- \( y \) required calculation height
- \( E_m \) Young’s modulus of Elasticity for metal
- \( E_c \) Young’s modulus of Elasticity for ceramic
- \( \vartheta_m \) Poisson ratio for metal
- \( \vartheta_c \) Poisson ratio for ceramic

ANSYS Mechanical APDL was used for modeling functionally graded materials. PLANE82 2-D 8-Node Structural Solid element was selected as element type for both cortical bone, and implant. PLANE82 element is a suitable choice for high accuracy of quadrilateral and triangular automatic meshes. In addition, it’s well suited to model curved boundaries as shown in Fig. 5.

The implant area was divided into small area by to do loop in ANSYS. Each area is considered as isotropic. The material property was calculated by Excel program as explained earlier.

The meshing is done with solid element; the meshed model is shown in Fig. 8. The mesh is refined significantly to capture accurate result. Step by step modeling will be presented as below.

Modal analysis is carried out for all implant material specified in Table 1. The modal frequencies are extracted with mode shapes (12 models). Block Lanczos method used for algorithm as it is recommended for most applications. Block Lanczos method has the ability to extract large number of modes (+40), and it can be used for complex models with mixture of solid/shell....etc.

### 3. RESULTS

Mode analysis and mode shape for five models will be discussed in this section. Modal analysis and shapes will be presented. Static analysis is performed for those models. Twelve shape modes are extracted for each. Only last four deformation shapes will be presented. The mode frequencies for the 12 modes are showing in Table 2. The mode shapes for each material is showing in Figs. 10-15 (only two modes are presented the others will be showing in the appendix). It can be noticed that the first six frequencies are (0) which is normal for the rigid body.

Hydroxyapatite (ceramic) natural frequency is lower than the Titanium natural frequency. It is noted that the frequency of functionally graded material for the implant (Ti-HA) is vary between the frequency of two basic materials (Hydroxyapatite and Titanium). The

| Material          | Modulus of elasticity GPa | Poisson’s ratio | Density \( \rho \) kg/m\(^3\) | Reference |
|-------------------|---------------------------|-----------------|-------------------------------|-----------|
| Cortical bone     | 14                        | 0.3             | 1300                          | [2]       |
| Titanium          | 110                       | 0.3             | 4430                          | [3]       |
| Hydroxyapatite    | 74                        | 0.27            | 3160                          | [4]       |
| Zirconium Oxide   | 205                       | 0.23            | 5725                          | [5]       |

![Fig. 2. Schematic view of FGM dental implant with graded material composition [1]](image-url)

**Table 1. Mechanical properties of materials used for the model**
Table 2. Frequencies for 12 mode shapes

| Mode | Pure Titanium (Hz) | FGM at x=0.01 Ti-HA (Hz) | FGM at x=0.5 Ti-HA (Hz) | Pure Zirconium (Hz) | Classic implant Hydroxyapatite (Hz) |
|------|------------------|------------------------|------------------------|-------------------|-------------------------------------|
| 1    | 0.341x10^{-4}    | 0                      | 0                      | 0                 | 0                                   |
| 2    | 266              | 266.01                 | 264.75                 | 258.51            | 319.9                               |
| 3    | 527.29           | 527.33                 | 502.52                 | 515.88            | 643.9                               |
| 4    | 633.28           | 633.71                 | 537.35                 | 610.25            | 746.89                              |
| 5    | 697.75           | 698.22                 | 644.42                 | 682.72            | 851.68                              |
| 6    | 823.53           | 823.96                 | 741.97                 | 800.96            | 985.84                              |
| 7    | 907.26           | 908.16                 | 797.69                 | 870.85            | 1057.2                              |
| 8    | 973.63           | 974.94                 | 808.16                 | 929.31            | 1109.2                              |
| 9    | 986.77           | 987.76                 | 846.26                 | 943.88            | 1157.3                              |
| 10   | 998.23           | 999.36                 | 923.1                  | 963.48            | 1172.6                              |
| 11   | 1084.9           | 1086.1                 | 944.05                 | 1037.9            | 1282.9                              |
| 12   | 1108.7           | 1110.1                 | 979.46                 | 1060.8            | 1298.7                              |

Frequency of FGM is decrease by increasing the content of Titanium and the opposite is applicable. On the other hand, the frequency of the implant classic marital has a higher frequency comparing to the all other material due to lighter weight. Fig. 14 is graphically presenting natural frequencies.

Fig. 4. ANSYS analysis process flow chart

A static analysis was carried out for the five models. The von Mises stress and deformation displacement was extruded using static analysis in ANSYS. A 100 N was applied on center of the implant in Y-direction Fig. 16. The displacement for the cortical bone was set at “0” on the bottom side area. The resulted stress and displacement are summarized on the below Table 4.

Fig. 5. PLANE82 2-D 8-node structural solid

Table 3 and Fig. 15 display the deformation shapes for implants. It is clearly that the natural frequency for the classic implant has a higher deformation comparing to other implant pure materials. For the FGM material, the deformation is fluctuating between the two basic materials and it is more near the higher weight which is the Titanium. This is because the content of each FGM is compound of both materials with different ratio.

Fig. 3. Schematic of implant
4. DISCUSSION

One of the major areas to be studied for dental implant stability is the material type. As it is known that each material has different properties which can be utilized for different purpose according to the desired application. So, the Titanium is used in dental implant because it has the ability of corrosion resistance and can be bonded with the living tissues. One of the big challenges today is to select the proper materials for dental implants to avoid the conflict between mechanical properties of engineered and natural biomaterials. This conflict usually produces bone remodeling problems. Functionally graded materials has been proposed as an upgrade that can reduce lot of these problems. It is clear from the results that stress amount is increasing on the more rigid implant material. The Zirconium implant has the highest stress with 15.548 MPa and lower displacement 0.00096X10^-5 mm. The FGM implant materials stress is higher when x=0.01 and lower stress when x=0.5. When the amount of Ti is increases the stress will increase and the displacement is decrease. It is observed that Hydroxyapatite has a lower stress and higher displacement. This because it is softer and more flexible when compare it with other models materials. Figs. 17-21, is representing the nodal solution and displacement deformed shape for the five modes. The harmonic analysis was performed for all five models. The number of sub-steps was selected to be 100. The force of 100 N was set to by in Y-direction at the center of bone area was fixed.

The frequency range was set between 0-6000 Hz. tow nodes were selected on the implant to extrude the frequency for each model. The below figs. 22-26 show the frequency response with the amplitude at Y-direction.

For Table 3:

| Mode | Pure | FGM at x=0.01 | FGM at x=0.5 | Pure | Classic implant |
|------|------|---------------|--------------|------|-----------------|
|      | Titanium (10^-5mm) | Ti-HA (10^-5mm) | Ti-HA (10^-5mm) | Hydroxyapatite (10^-5mm) | Zirconium (10^-5mm) |
| 1    | 1.4951 | 1.4977 | 1.2581 | 1.7702 | 1.3151 |
| 2    | 2.5112 | 2.5144 | 2.0981 | 2.9738 | 2.2082 |
| 3    | 3.0942 | 3.1007 | 2.4158 | 3.6965 | 2.7766 |
| 4    | 5.4006 | 5.4135 | 4.3662 | 6.4776 | 4.8670 |
| 5    | 3.2291 | 3.2358 | 2.5205 | 3.7606 | 2.7382 |
| 6    | 3.0023 | 3.0135 | 2.8483 | 3.4633 | 2.4279 |
| 7    | 3.0551 | 3.0583 | 3.8684 | 3.5825 | 2.6522 |
| 8    | 4.6928 | 4.6886 | 3.4777 | 4.4889 | 2.7607 |
| 9    | 3.7743 | 3.7676 | 3.2304 | 4.2164 | 2.5737 |
| 10   | 4.0988 | 4.1163 | 3.5235 | 4.5863 | 2.9777 |
| 11   | 3.0822 | 3.0371 | 3.9301 | 4.8428 | 4.2740 |
| 12   | 4.0733 | 4.0844 | 4.2642 | 4.8058 | 4.5424 |

For Table 4:

| Pure | FGM at x=0.01 | FGM at x=0.5 | Pure | Classic implant |
|------|---------------|--------------|------|-----------------|
|      | Titanium | Ti-HA | Ti-HA | Hydroxyapatite | Zirconium |
| V. Mises | 12.9617 | 13.7535 | 11.1839 | 11.4199 | 15.548 |
| Displacement | 0.001092 | 0.001093 | 0.00091 | 0.001208 | 0.00096 |
Fig. 7. Defined the area for implant and cortical bone

Fig. 8. Meshed model
Fig. 9. Mode shapes for (Titanium)

Fig. 10. Mode shape (FGM Ti-HA) at x=0.01 check
Fig. 11. Mode shape for (FGM Ti-HA) at x=0.5

Fig. 12. Mode shape hydroxyapatite
Fig. 13. Mode shape for zirconium oxide

Fig. 14. Natural frequencies for 12 mode shapes

Fig. 15. Maximum displacements of deformed shape for the first 12 mode shapes
Fig. 16. 100 N is applied in Y-direction (static analysis)

Fig. 17. Static deformation for (Titanium)

Fig. 18. Static deformation (FGM Ti-HA) at x=0.01

Fig. 19. Static deformation for (FGM Ti-HA) at x=0.5

Fig. 20. Static deformation for hydroxyapatite
Fig. 21. Static deformation for zirconium oxide

Fig. 22. Frequency response for titanium

Fig. 23. Frequency response for FGM Ti-HA at x=0.01

Fig. 24. Frequency response for FGM Ti-HA at x=0.5

Fig. 25. Frequency response for hydroxyapatite
The performed harmonic analyses have been carried out for two nodes which were specified. Thus, the resulted plots can provide the deflection in those nodes at certain frequency. It is clearly that the FGM is moving similar to the titanium but with lower deflection at that area.

5. CONCLUSION

The functionally graded material was considered in two models using ANSYS15.0 APDL. Both are for the same materials, Ti-HA with different ratio in each. The natural frequency and modal shapes were extracted for the first 12 models. Generally, it was noticed that the natural frequency, modal shape, stresses and displacement vary between the two basic materials in the FGM dental implant but more near to the titanium. It strongly depends on the concentration of the material in the model. When the ration for the titanium increases for the FGM implant the frequency decreases due to the higher weight and the opposite is applicable. There is a need for a future research work of the dental implant to be optimized in case of functionally graded material. The tools for designing and simulating a desired material property are available on hand which will help to have a more stable, safe, costly effected dental implant. Also, there is a need to study numerically and experimentally the damping effect of the FGM implant comparing to the conventional dental implant.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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