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Vibrational characteristic of heart stent using finite element model

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Abstract-- Heart stents are widely implemented for those patients who suffer from chronic heart diseases. The primary failure of this biomedical device is its collapse during the operation. The most common sources of this failure come from the nature of the stent material and surgery conditions. The focus of the paper is on the vibrational behavior of the integrated part of the artery and stent by simulating the operating condition using a finite element model. Modal analysis of the proposed model is performed to determine the natural frequencies and corresponding mode shapes of the system. In addition, harmonic analysis of the model is performed to derive the kinematic characteristics, including displacement, velocity, acceleration, and directional stresses, by considering the effect of blood pressure. Finally, the spectral analysis of the complex is applied to investigate the influence of random vibrational excitations on the system by using power spectral density (PSD) analysis.

Keywords---vibration, finite element method, stent, modal analysis, spectrum analysis.

Introduction

Coronary artery diseases are the most prevalent types of vascular disease, which cause narrowing or blockage of coronary vessels. Besides the medications, a widely used treatment for this issue is implementing a coronary stent in blockage

to supply blood flow to the heart. However, due to the interaction of intervascular and external loads with implemented stents, fracture or inefficiency of the stents may occur. Hence, the mechanical behavior of stents after implementation must be considered to optimize the design. The vibrational analysis of inserted stent can be studied to obtain two achievements. First, for proper design considering external parameters affecting the stability of stents after being in place, and the second is the application of stents to detect or adjust the unwanted changes in the stent or its environment conditions applying smart or active stents. During the stent operation, the most crucial concerns are in-stent restenosis (ISR) and stent fracture (SF), which may cause malfunction and harmful consequences. These harmful events may occur due to vascular pulsation (VP) and vascular dynamic bending (VDB) due to external stimuli such as blood flow and pressure, change in breathing, and heart condition due to daily activities or diseases arrhythmia or magnetic fields exposure. Numerous studies have been conducted on the free vibration and forced harmonic response of shells with different cross-section shapes [1-3]. Amabili et al. [4-5] studied nonlinear free and forced vibration of empty and fluid-filled circular cylindrical shells. Rabbani et al. [6] presented an analytical model based on Navier's equation to analyze free vibration of infinity long thick-walled hollow elliptical cylinders. Ferecentese et al. [7] focused on modeling fluid-structure interaction and wave propagation issues in the artery stents. They indicated the possibility of change in wave propagation in the arterial network due to reinforcement of arteries with stents, which can lead to restenosis. Papathanasiou et al. [8] compared the effect of the stent periodic structure on wave reflection and transmission of a single long and two successive stents. Salman and Yazicioglu [9] studied vibro-acoustic waves propagating through surrounding soft tissue due to constricted arteries' vibration to develop a non-invasive method to detect vascular stenosis. Their results indicated a significant increase in response amplitude as a result of severe stenosis at higher frequencies. Xu et al. [10] conducted a finite element analysis to study the mechanical response of cardiovascular stents under vascular dynamic bending (VDB) and compared obtained results with those of vascular pulsation (VP). The significant role of VDB on fatigue and long-term mechanical properties of implemented stents was obtained from their results. Ma and Shang [11] presented mathematical modeling for the breathing vibration problem of stents in order to modify the vascular stent design. They derived the equation of vibration for vascular stents from the Flugge shell theory. When a coronary stent is mounted, the in-stent restenosis may be unpreventable. Therefore, several studies are conducted to detect unwanted changes in a stent after placement. In addition, these studies could lead to modern technologies to monitor other vital parameters of the human body. Jaganathan et al. [12] conduct a FEM modal analysis on metallic coronary stents. They compared natural frequencies of different metallic materials while neglecting the effect of blood pressure and vibration of blood vessels. A comparison of natural frequencies of different metallic cardiac stents considering cyclic loading, including systolic-diastolic pressurization and bending, was done by Auricchio et al. [13]. Chen et al. [14] developed a smart stent equipped with microscale sensors and a wireless interface to monitor stent restenosis. Their model was based on changes in the resonant frequency of stent at the normal level and in-stent restenosis due to a change in local blood pressure. A radio-frequency interrogation method for sensor-integrated smart stent implants based on transient resonance to detect stent restenosis was

reported by Brox et al. [15]. Their results showed that their method is applicable to wireless detection of stent conditions after implementation. Vishnu and Manisavagam [16] applied for a review on smart stents with sensors. They indicated stent endothelialization could be detectable by changing the resonance frequency of the sensor attached to the stent due to contact with endothelial cells and stent. Recently, the application of stents to remove in-stent restenosis has been taken into consideration. The development of an active stent moving by ultrasonic vibration in order to remove stent plaque has been done by Nishizawa and Tayoma [17]. The function of their model is based on the vibration of a coil-shaped stator which receives its motion from two cylindrical receivers.

Due to the dependency of the aforementioned content on the category of vibrational behavior of cardiac stents and the lack of sufficient information and multiple simplifications in this regard, in this study, a FEM modeling to analyze the vibrational characteristics of the applied heart stent is presented. To do so, natural frequencies and mode shapes are obtained from the modal analysis. Then a harmonic analysis followed by spectrum analysis to study the response of the structure under the action of loads using ANSYS software is presented.

Methodology

Due to the complexity of the vessel and stent modeling, it was modeled in Workbench and exported to the APDL to analyze it in ANSYS/APDL software. Figure 1 depicts the final modeling of the stent and the artery which are established in Ansys Workbench.

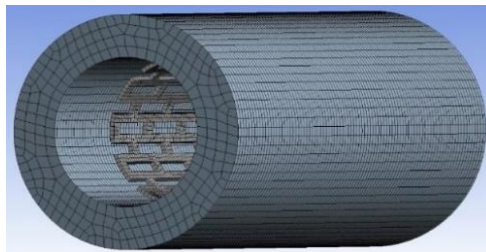


Figure 1 Completed artery and stent model.

Since this paper focuses on proposing the vibrational analysis method of coronary stents, due to simplifying the model to reduce simulation processing time, one particular real-world pattern of the stent has been modeled in ANSYS, and various types of analysis are performed on this model. In addition, the SOLID 186 element (20 nodes per element) is selected to achieve the optimal precision of the results, and the model is refined to meet the appropriate convergence requirements of less than 1%. In the presented model, steel material has been selected to design the stent. The pattern of the stent is shown in Figure 2. Figure 3 illustrates the final mesh refinement of the stent in ANSYS APDL. Mechanical properties and dimensions of stent and artery are presented in Table 1 and Table 2, respectively.

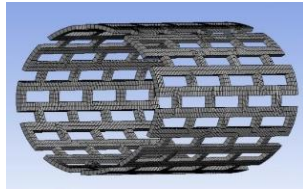


Figure 2 Stent pattern

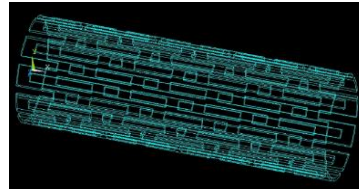


Figure 3 Final mesh refinement of the stent in the APDL

Table 1 Mechanical properties of stent and artery

| | Stent | Artery |
|--------|---------|---------|
| ρ | 7860 | 1200 |
| E | 207 GPa | 800 kPa |
| ν | 0.3 | 0.49 |

Table 2 Dimensions of model

| Entities | Stent | Artery |
|------------------|-------|--------|
| Length | 10 | 18 |
| Thickness | 0.1 | 1.8 |
| Inside Diameter | 3 | 3.2 |
| Outside Diameter | 3.2 | 5 |

Modal Analysis

The modal analysis would be conducted when the purpose is to determine natural frequencies and the corresponding mode shapes due to the free vibration of an undamped system. This type of analysis is not applicable to determine stress, velocity, acceleration, and displacement. The governing equation of motion for free vibration of an undamped system may be written as follow:

$$[M][\ddot{U}] + [K][U] = 0 \quad (1)$$

which M is the total mass of the system, K is the stiffness and U is the displacement. A harmonic behavior can be expected to describe this vibrational system. As a result, the response of free vibration can be determined as the following:

$$[U] = \{\psi\}_i \cos(\omega_i t) \quad (2)$$

Wich $\{\psi\}_i$ are the eigenvectors, and ω_i is the frequency. Substitution of equation (2) in equation (1) results in:

$$([K] - \omega_i^2 [M])\{\psi\}_i = \{0\} \quad (3)$$

The natural frequencies of the system can be obtained by solving the first term of equation (3), which are the eigenvalues of the system. System's mode shapes may be obtained by substituting each eigenvalue into equation (3) and solving the equation to derive vector $\{\psi\}_i$.

Harmonic Analysis

When the harmonic analysis is performed, it is assumed that the displacements and loads change based on a harmonic pattern at equal frequencies while the other vibrational characteristics of the system, such as mass effects, damping, and stiffness, remain constant. As a result, equation (1) can be rewritten as follow, while the effect of structural damping, $[C]$, is considered.

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{F\} \quad (4)$$

The response function due to the presence of the structural damping can be predicted as the following:

$$\{U\} = \{U_{max}(\cos \varphi + i \sin \varphi)\}e^{i\omega t} \quad (5)$$

Where the terms including φ indicate phase shift. The equation of force vector will be:

$$\{F\} = \{F_{max}(\cos \alpha + i \sin \alpha)\}e^{i\omega t} \quad (6)$$

Substitution of equations (5) and (6) in equation (4) results in the following response equation:

$$([K] - \omega^2[M] + i\omega[C])\{U\} = \{F\} \quad (7)$$

Spectrum Analysis

The spectrum analysis aims to measure the value of input excitation with respect to the frequency in a system's frequency range. The methods of spectrum analysis are categorized into four classifications. Single-point (SPOT, SPRS), multiple-point (SPOT, MPRS), the dynamic design analysis method (DDAM), which has the deterministic spectral responses, and power spectral density (PSD) method, which has non-deterministic random vibration. In this study, the PSD method is conducted, leading to achieving the foremost description of the vibrational behavior of the system, As the primary concept of this paper is based on the randomly applied loads. The main concept of PSD is to investigate the responses of the modal behavior statistically. Modal analysis is a prerequisite of spectrum analysis. Four steps are executed to solve the problem based on the PSD method with Ansys software. The first step is to recall the system's natural frequencies obtained from the modal analysis. This step is done to determine the frequency domain. The next step is to assume an arbitrary excitation pattern based on a primary range of the natural frequencies. Thus, calculating the participation factor of the system is the next step. The final step is solving the corresponding equations to obtain the random vibration responses for the first, second, and third standard deviations ($1\sigma, 2\sigma, 3\sigma$).

Results and Discussion

Modal Analysis

As mentioned before, the purpose of modal analysis is to determine the natural frequencies as well as corresponding shape modes of the system. This purpose is classified into two cases, namely, the integrated complex of artery and stent and considering the only stent. This classification is applied to investigate the influence of arteries on the system's natural frequencies. Figure 4 and Table 3 and show the first 10 frequencies of the integrated system (stent and artery) in comparison with the natural frequencies of the stent.

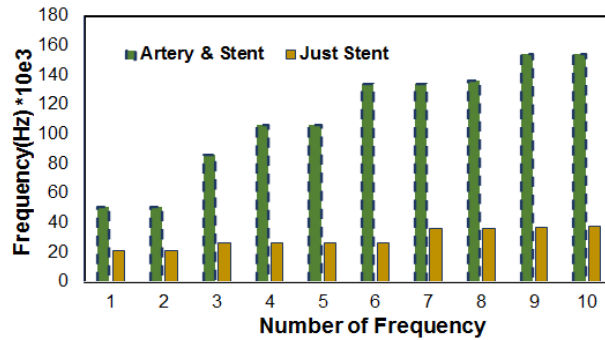


Figure 4 Comparison of natural frequencies

As can be seen in the results, the natural frequencies of the integrated system are significantly higher than the natural frequencies of the stent. It is coming from this fact that by consideration of the artery around the stent, the total stiffness of the integrated part would be more than without artery case, while the total mass of the system is not increasing notably. So, in this state, the natural frequencies of the integrated part would be dramatically increased. Figure 5 illustrates the corresponding mode shapes of the integrated part for the first six modes of vibration. Also, to present the results understandably, the mode shapes of the stent are shown separately.

| Mode Number | Frequency (Hz) | |
|-------------|----------------|------------|
| | Artery & Stent | Just Stent |
| 1 | 50536 | 20785 |
| 2 | 50537 | 20786 |
| 3 | 85674 | 26094 |
| 4 | 106521 | 26095 |
| 5 | 106531 | 26411 |
| 6 | 134160 | 26415 |
| 7 | 134180 | 35751 |
| 8 | 136420 | 35751 |
| 9 | 154180 | 36891 |
| 10 | 154190 | 37980 |

Table 3 Natural frequencies of the system

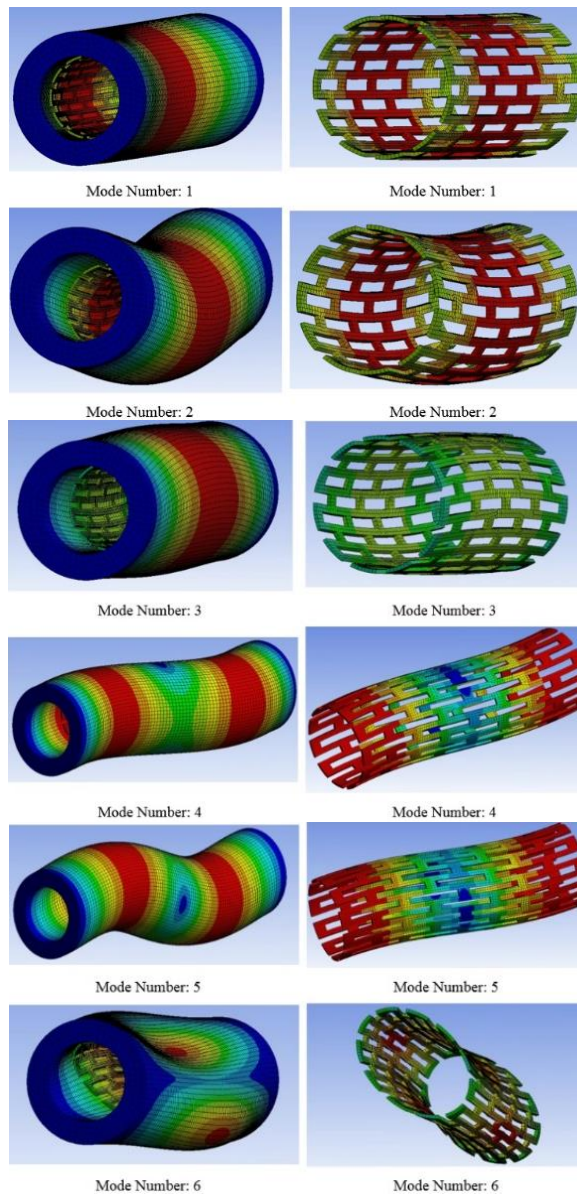


Figure 5 Mode shapes of the stent and integrated system

Harmonic Analysis

As mentioned in the previous sections, harmonic analysis is applied to obtain the vibrational behavior of the stent during applying harmonic loads such as heartbeat and blood pressure. In this study, the blood pressure would be considered as a surface pressure with the quantity of 13.3 (kPa), which is applied on the interior surface of the stent and artery. Figures 6 to 8 show the value of stress components in three directions (x, y, z) for a node at the middle and top of the stent, respectively. As can be seen in these figures, the x -component of stress (longitudinal stress along the axial direction of the stent and artery) is

significantly more than the other directions. Also, the amount of y-component and z-component of the stresses are almost the same.

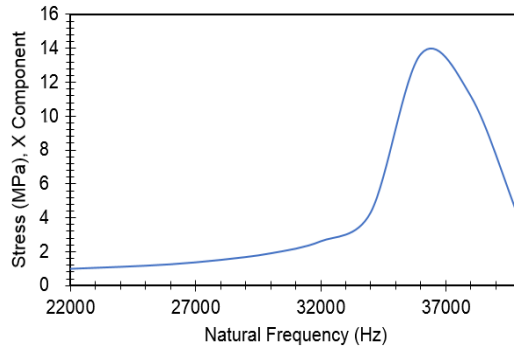


Figure 6 x-component of stress

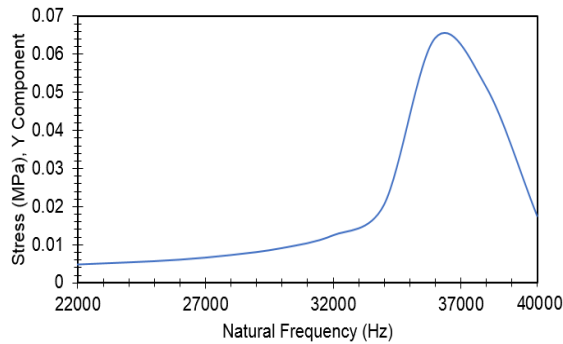


Figure 7 y-component of stress

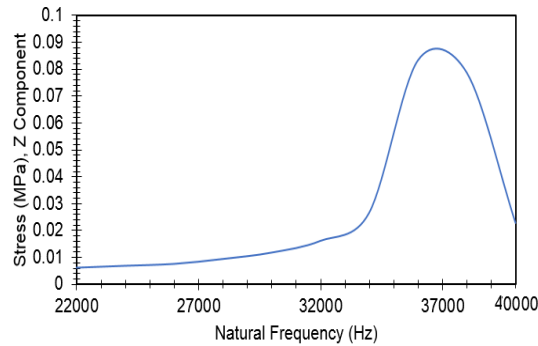


Figure 8 z-component of stress

Additionally, Figures 9 to 11 illustrate the amount of displacement, velocity, and acceleration of a similar point in the z-direction. As shown in these graphs, it could be predicted that there is a very low value of displacement, although there is a remarkable amount for the acceleration, which may generate significant stress in the x-direction (Figure 6).

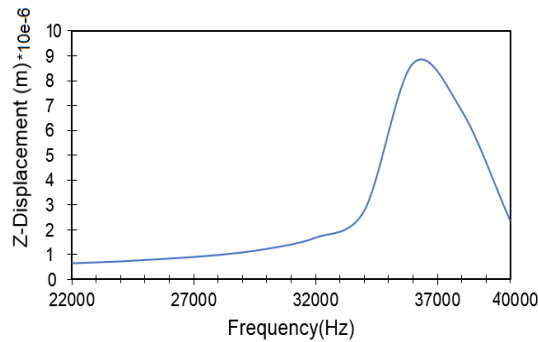


Figure 9 Displacement of the middle point of the stent in the z-direction

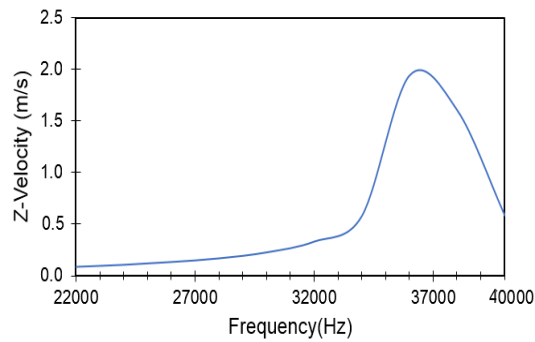


Figure 10 Velocity of the middle point of the stent in the z-direction

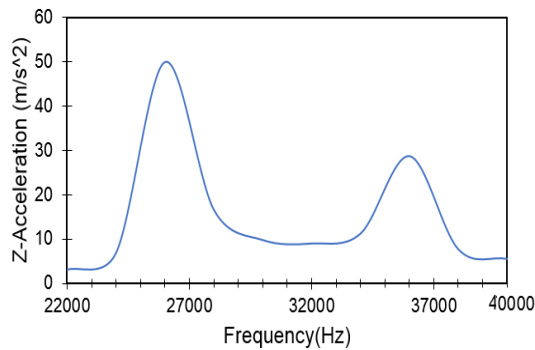


Figure 11 Acceleration of the middle point of the stent in the z-direction

Spectral Analysis

Spectrum analysis has been performed as a primary objective of the research. To perform this analysis, the process explained in section 2.3 has been followed accurately. Table 3 shows the values of the random excitation in the z-direction. As a matter of fact, this excitation has been applied on the stent to make a random load case in the z-direction and in the range of 10 first natural frequencies of the system shown in Table 4.

Table 4 The pattern of excitation

| Frequency (Hz) | Acceleration (m/s^2) |
|----------------|--------------------------|
| 22000 | 1 |
| 25000 | 1 |
| 28300 | 1.5 |
| 31200 | 1.8 |
| 31800 | 1.2 |
| 32788 | 1.3 |
| 35000 | 1.45 |
| 37564 | 1.35 |
| 38765 | 1.2 |
| 39894 | 1.1 |

Figures 12 and 13 show the nodal solutions of the first and last frequencies of the spectrum results. Additionally, Figure 14 shows the spectrum PSD acceleration response of the integrated part of the stent an artery based on the frequencies. The result shows the maximum acceleration of the integrated part concerning the first excitation in the PSD unit. Also, the probability of occurrence in this analysis is based on the first standard deviation.

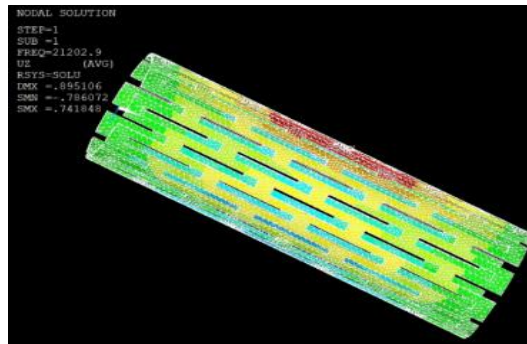


Figure 12 Spectrum nodal solution for the first frequency

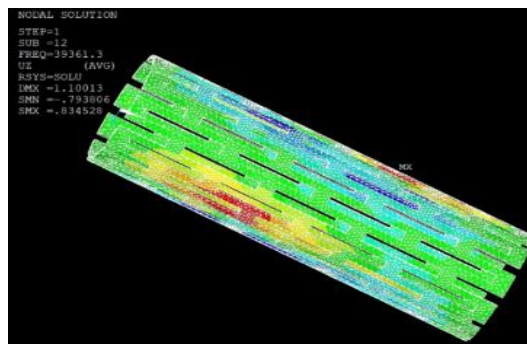


Figure 13 Spectrum nodal solution for the last frequency

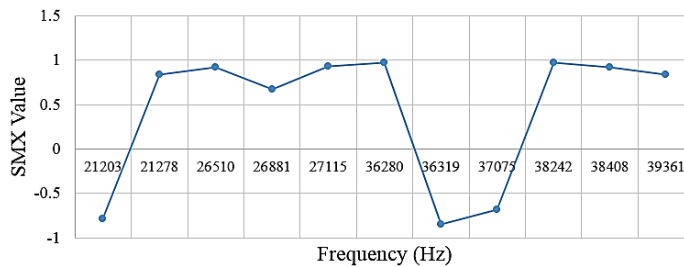


Figure 14 Spectrum acceleration result for the stent in PSD acceleration unit

Conclusion

In this study, a finite element model is presented to investigate the vibrational behavior of cardiac stents. The pattern of the stent is selected according to an actual commercial stent. After performing modal analysis to obtain natural frequencies and mode shapes, a harmonic and spectrum analysis to study the behavior of the system in the presence of pulsating and random loading, is conducted. The presented model can be applied to modify the coronary stents design as well as active and smart stents. Due to the complexity of solid-fluid interaction as a result of blood flow, the effect of blood is stimulated by considering the internal pressure. Hence, the effect of actual blood flow in FE simulation will be the main purpose for future study.

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