Estimation and Comparison of Natural Frequency of Coronary Metallic Stents using Modal Analysis

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Abstract

Objective: A recent report states that more than 2,000,000 stents are used worldwide per year. Here, we examine the structural integrity and modal analysis was done to estimate the natural frequency. Methods: An S-linked stent was modelled using ANSYS workbench. For this study three commonly used stent materials namely stainless steel (316L), cobalt-chromium alloy (CoCrMo) and titanium alloy (Ti₆Al₄V) were chosen. The modal analysis was done to find the natural frequencies for each bio-metal chosen. The natural frequencies were significantly different (P<0.05) for the three metallic stents at each corresponding modes. Result: From a comparative study it is evident that the natural frequency acquired depends on the property of the chosen materials. The young's modulus and density of titanium alloy is the least, followed by 316L and cobalt chromium alloy, which is also revealed in the natural frequency pattern acquired. The vibrating modes at each frequency showed pronounced changes in their shapes for every stent material. The natural frequencies do not with the resonate and with the natural frequency of the blood vessels. Conclusion: The medical product designers for designing new stents with better structural integrity before stent insertion, substituting in vivo experiment that is difficult and unpractical, may use this work.

Keywords: Cardiovascular Stent, Coronary Artery Obstruction, Modal Shapes, Natural Frequency, Structural integrity

1. Introduction

Coronary Artery Obstruction (CAO) is the most recognizable vascular disease. It is typically due to atherosclerotic occlusion of coronary arteries. Atherosclerosis is caused by plaque building up along the inner walls of arteries, leading to ischemia in turn coronary artery obstruction. Coronary artery disease has been alleged as a “Man’s disease” but now has been predicted in women due to inimitable risk factors including those related to pregnancy and auto immune diseases. Left coronary artery obstruction is more widespread than right coronary artery obstruction (83.3% Vs 12.5%)¹.

Coronary artery stent increasingly used for coronary artery stenosis and can also be used for peripheral blood vessels. To prevent the elastic retrenchment of the arteries that occurs instantly after the elimination of artery obstruction, characteristically a coronary stent is placed. Stent is a mesh tube inserted to prevent the localized blood flow constriction in the arteries of the heart by the course of action named angioplasty². Metallic stents made up of paramagnetic materials such as stainless steel (316L), titanium alloy (Ti₆Al₄V) and cobalt chromium alloy (CoCrMo) are used to treat arterial occlusion. Stents
are usually indistinguishable except their linking configuration explicitly S, N, W and modified W, affecting the flexibility of stents.

Every object vibrates at a particular frequency known as the natural frequency. This natural frequency is usually interrelated to the mechanical property of the object. Finite Element Method (FEM) is the most valuable numerical investigation tool for Engineers, involving some nature of governing integral statement which is transformed to a matrix system. The main advantage is that it can be applied to arbitrary shapes in any dimensions and the shape can be made up of any materials. Finite element analysis consists of computer modelling that is analyzed for specific results that are precise and fast. Finite element analysis of stents investigates the mechanical properties of the stents and formative the biomechanical interaction between the stent and arteries.

The aim of the study is to compute the modal analysis and comparing the mechanical characteristics of the stent material. We build up a testing and simulation method for the assessment of structural integrity and the biomechanical implication of the entrenched stents.

2. Materials and Methods

2.1 Material Chosen

In our project we have chosen three materials namely titanium alloy (Ti₆₆₄ₐ₄₉), stainless steel (316L) and cobalt chromium alloy (CoCrMo) based on its common usage. Ti₆₆₄ₐ₄₉ ELI is a higher-purity (“extra-low interstitial”) version of Ti₆₆₄ₐ₄₉, with lower specified limits on iron and the interstitial elements C and O. It is a combination of alpha and beta alloy. Ti₆₆₄ₐ₄₉ has been the material of choice for many medical and dental applications due to its excellent biocompatibility. 316L austenitic stainless steel (ASTM F 138/139), despite its greater susceptibility to crevice corrosion compared to other common metallic biomaterials has over decades of use proved acceptable and the metal of choice for fracture repair devices. Cobalt-chrome or Cobalt-Chromium (CoCr) is a metal alloy of cobalt and chromium. Cobalt-chrome has a very high specific strength and is commonly employed in gas turbines, dental implants and orthopedic implants. CoCrMo is usually the dominant alloy for total joint arthroplasty. CoCrMo alloys cast to a final form (high-C) are made by investment casting procedures (the lost wax process). This involves the simultaneous casting of a number of components (e.g., femoral stem or ball components for hip implants) onto a so called ‘casting tree’.

2.2 Specifications

The ANSYS workbench modelling tool is used to model the stent. The inner diameter of the stent is 1.5×10⁻³ m and the length is 7×10⁻³ m, whereas the width and thickness of the cross-section is 110×10⁻⁶ m and 80×10⁻⁶ m and the stent can be considered as an orthogonally anisotropic cylindrical thin shell, shown in Figure 1.

The properties of the metals specified are young’s modulus, poisson’s ratio and the yield strength, as they play a key role in designing. The young’s modulus of stainless steel alloy (316L) stent is 196×10⁹ Pa; poisson ratio 0.3 and the yield strength 290×10⁶ Pa. The young’s modulus of titanium alloy (Ti₆₆₄ₐ₄₉) stent is 110×10⁹ Pa; poisson ratio 0.3 and the yield strength 880×10⁶ Pa. The young’s modulus of chromium alloy (CoCrMo) stent is 210×10⁹ Pa; poisson ratio 0.3 and the yield strength 450×10⁶ Pa as listed in the Table 1.
2.4 Statistical Analyses
Statistical analysis of the results was carried out using graph pad prism. One way ANOVA was performed to estimate the statistical significance. A probability value of $P<0.05$ was considered as statistically significant for the three different metallic stents we have compared.

3. Results
Modal analysis in structural mechanics is to determine the natural mode shapes and to study the dynamic properties of an object or structure under vibrational excitation, measuring and analyzing the dynamic response of structures and or fluids when excited by an input. At or near the natural frequency of a mode, the overall vibration shape (“operating deflection shape”) of a structure will tend to be dominated by the mode shape of the resonance. The bar metal stent was subjected to modal analysis and their natural frequencies are enlisted in Table 2, according to the titanium alloy, stainless steel alloy and cobalt chromium alloy.

![Analysis procedure flow.](image)

**Figure 2.** Analysis procedure flow.

| Material | Elastic mod (Gpa) | Poisson ratio | Density (g/cm³) | Yield Strength (Mpa) | Ultimate Strength (Mpa) |
|----------|------------------|---------------|-----------------|---------------------|------------------------|
| Ti₆Al₄V  | 110              | 0.3           | 4.5             | 880                 | 950                    |
| 316L     | 196              | 0.3           | 7.85            | 290                 | 558                    |
| CoCrMo   | 210              | 0.3           | 8.3             | 450                 | 655                    |

**Table 1.** The mechanical properties of chosen cardiovascular stent materials
Table 2. Natural frequencies of Ti₆Al₄V, 316 L, CoCrMo metal stents at five different modes

| Materials | Mode 1       | Mode 2       | Mode 3       | Mode 4       | Mode 5       |
|-----------|--------------|--------------|--------------|--------------|--------------|
| Ti₆Al₄V   | 1022.5±1.06  | 1591.1±0.20  | 3669.0±0.83  | 5210.3±1.27  | 5278.6±0.54  |
| 316 L     | 1033.4±0.50  | 1608.1±1.07  | 3708.1±0.26  | 5265.8±0.34  | 5334.8±0.48  |
| CoCrMo    | 1040.3±1.20  | 1618.7±1.05  | 3732.7±0.73  | 5300.8±1.25  | 5370.3±0.89  |

Mean differences are significant for the three materials at P<0.05. Data represents mean ±SD.

3.1 Mode Shapes

The five mode shapes of the titanium alloy (Ti₆Al₄V) stent are given in Figure 3, the vibrating frequencies ranging from 1022.5 Hz to 5278.6 Hz.

The five mode shapes of the stainless steel alloy (316L) stent are given in Figure 4, of frequencies varying from 1033.4Hz to 5334.8 Hz.

The five mode shapes of the cobalt chromium alloy (CoCrMo) stent are given in Figure 5, of frequencies from 1040.3 Hz to 5370.3 Hz.

4. Discussion

Finite element analysis is a technique that full-fill the needs of the medical product designer. This method authorizes the designer to rapidly access design before a metal is selected from the results it is revealed. The natural frequencies amend not only with the materials but also with the dimensions, link configurations, load constraints used for modelling the stent\textsuperscript{15}. When the stainless steel stent was subjected to finite element analysis with different load constraints ranged from 50 kgf/mm\textsuperscript{2} to...
Figure 4.  Mode shapes and natural frequencies of 316 L vascular stent at five different modes.

Figure 5.  Mode shapes and natural frequencies of CoCrMo vascular stent at five different modes.
73 kgf/mm², proves that the natural frequency shifts in accordance with the load applied. In our work, the stent modelled and subjected to modal analysis has a constant dimension, link configuration and unchanged load constraints with varying material properties. The metallic properties of our interest are young's modulus and density. The resulted natural frequencies attained are in accordance with the properties of the metallic materials. As shown in the Table 2 the natural frequency of the stent depends on the young's modulus and density of the material which they are made from. The young's modulus and density of titanium alloy is the least, followed by 316L and cobalt chromium alloy which is also revealed in the natural frequency pattern acquired.

It is a common knowledge that there should be no resonance between the stent placed and the blood vessel where it is inserted. The vibrational frequency of the blood vessels varies in the range of 1-2 KHz depending on the pulsatile and turbulent blood flow, which does not coincide with the natural frequency of the vascular stent. It is clear from the obtained results that the vibrational frequencies of stent do not coincide with the natural frequency of blood vessel, thereby diminishing the risk of resonance. The damaged structures have different natural frequency from the flawless structure for which the calculated vibrating frequency may be considered as the reference value. Vibrations from the vehicle may also damage the inserted stent during the travel of a person undergone angioplasty. The lateral vibrational frequency ranges from 1-2 Hz and vertical vibrational frequencies ranging from 2-16 Hz varying with the acceleration and the road surface. Past research has shown that heavy vehicle ride is most sensitive to excitations of the low frequency modes in the range 1-8 Hz. The same condition goes for the heavy exercise machines like treadmill with a highest vibrating frequency of 50 Hz, where as the result obtained from the analysis has a higher range thus, safe for the patients with implanted stents. Ultrasonic cleaning is one of the processes prevalent throughout the medical equipment industry. It is eminent that a small device with a resonant frequency near that of ultrasonic cleaning frequency is vulnerable to significant failure. Finite element analysis is competent of accurately predicting the vibrating frequency of medical devices, permitting a manufacturer to make changes in designing the medical implant and to avoid resonant conditions that could lead to significant mechanical damage and premature failure. Different techniques that keep away from ultrasonic-induced damage have been used effectively in the electronics manufacturing industries and could be employed in the medical device industry to avoid the problems associated with ultrasonic cleaning induced resonance and exhaustion. Hence when a vascular stent is modelled with the proposed metal and dimensions the natural frequency found is to be taken under thought to clean the stent using ultrasound waves.

5. Conclusion

The inner diameter of the stent we modelled is $1.5 \times 10^{-3}$ m and the length is $7 \times 10^{-3}$ m which may be placed in the Left Anterior Descending artery (LAD) after removing the obstruction in the artery. The stent was subjected to modal analysis using finite element method and the mechanical behaviour was studied. The study of the mechanical behaviour proposed could help in designing new stents or analyzing actual stents to guarantee frequency response and structural integrity, supporting the real time experiments, which are unfeasible. These results are assuring and useful in the study of the vibrational performances of the stent itself thus providing the health specialist, a scheme based on the patient's lifestyle. In the future, the proposed modal analyzed stents can be adapted for fluid-structural and stent-artery interaction analyses.

6. References

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