ARTIFICIAL HEART VALVE MODEL

INTRODUCTION

The heart is a muscular pump with four chambers and four heart valves. The upper chambers, the right atrium and left, are thin walled filling chambers. Blood flows from the right and left atria across the tricuspid and mitral valves into the lower chambers (right and left ventricles). The right and left ventricles have thick muscular walls for pumping blood across the pulmonic and aortic valves into the circulation. Heart valves are thin leaflets of tissue which open and close at the proper time during each heart beat cycle. The main function of these heart valves is to prevent blood from flowing backwards.

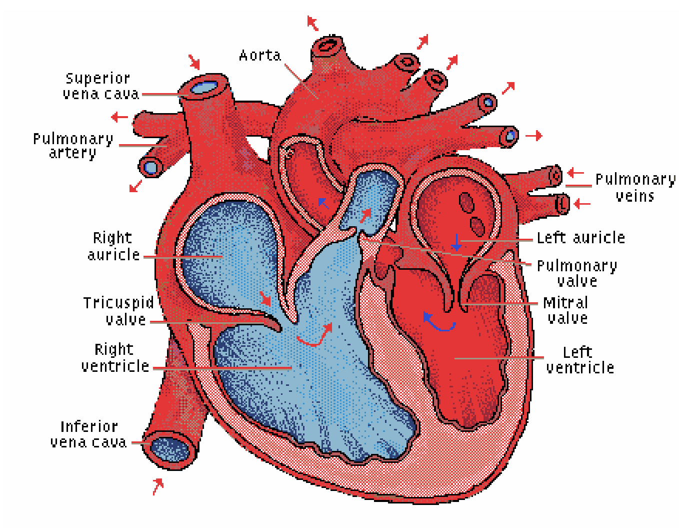


Figure 1 The Human Heart

The heart valves suffer two main types of diseases. One of them is the narrowing of the aortic valve (Aortic Stenosis). When the degree of narrowing becomes significant enough to impede the flow of blood from the left ventricle to the arteries, heart problems develop. Another medical condition is one in which the valve doesn't close completely, causing backflow. This is called incompetence or regurgitation.

ARTIFICIAL HEART VALVES

Artificial heart valves are usually implanted when valve disease leading to stenosis or incompetence is indicated. These valves are either mechanical or made from other biological tissue (usually pigs).

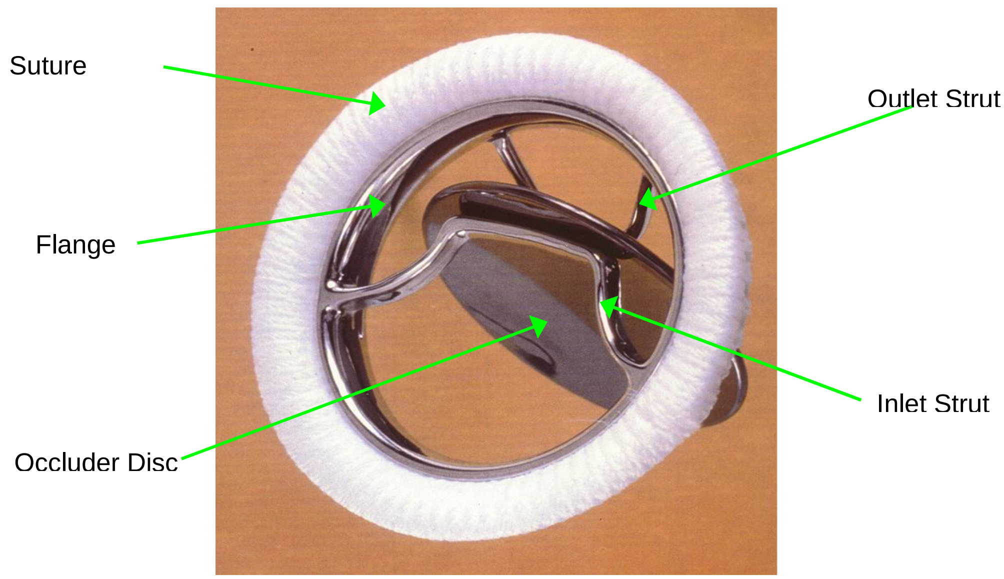


Figure 2 The BSCC Artificial Heart Valve

One type of mechanical valve called the Bjork Shiley Convexo Concave (BSCC) heart valve was widely implanted between 1979 and 1986. These valves have a carbon occluder disc held in place by two metallic struts. Of the two struts, the inlet strut is integral to the valve suture ring, while the other strut called the outlet strut is welded to the suture ring. In rare instances, fatigue and other factors caused by cyclical stresses cause the welds to fracture at one of the ends. Such a condition is called as Single Leg Separation (SLS). Although the valve can continue to function under these conditions, it increases the stress concentration on the intact end of the welded strut and it is uncertain as to how long the other end of the strut can remain intact. Fracture at both ends will cause detachment of the disc from the rest of the valve, leading, in almost all cases, to fatality. There is considerable interest, therefore, in the development of methods for assessing the state of the valve in general and the condition of the outlet strut weld.

EMAT Concept

The EMAT (electromagnetic acoustic transducer) approach [1] for detecting SLS in BSCC heart valves involves excitation of the strut resonance modes using electromagnetic methods. Two excitation coils are used, each generating an electromagnetic field. If the coils are placed perpendicular to one another and are both perpendicular to the plane of the heart valve, then one coil will generate a current in the heart valve ring. This current in the second coil's magnetic field will cause a force to be generated on the ring.

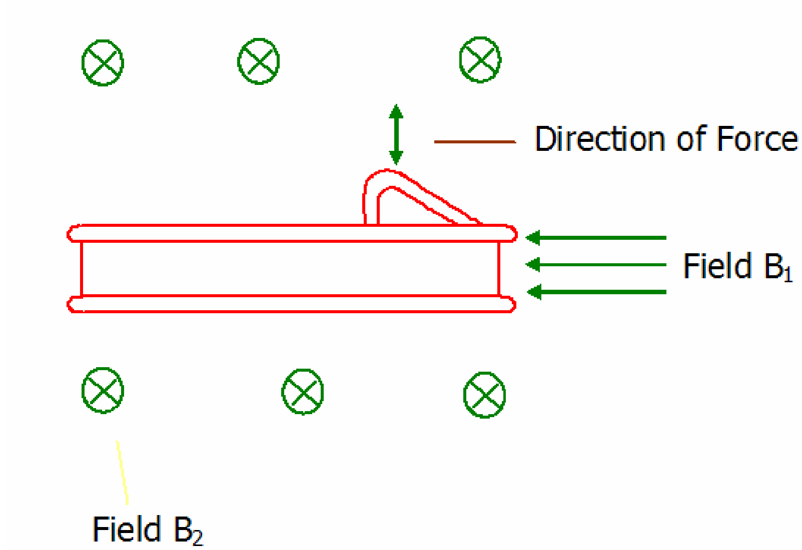


Figure 3 The EMAT Test

$$B_1 = |B_1|\sin(\omega_1 t)$$
$$B_2 = |B_2|\sin(\omega_2 t)$$
$$F_{vib} = \frac{(|B_1||B_2|\omega_2)}{Z} \times L \times A \times \cos(\omega_2 t) \times \sin(\omega_1 t)$$
$$= \frac{(|B_1||B_2|\omega_2)}{Z} \times L \times A \times \frac{1}{2}\left[\sin((\omega_1 + \omega_2) \times t) + \sin((\omega_1 - \omega_2) \times t)\right]$$

Here F_{vib} is the force of vibration of the ring, Z is the impedance of the ring, L is the effective conducting path length and A is the area of cross-section. Therefore by choosing ω_1 and ω_2 at a correct difference from each other, the ring can be mechanically excited at any frequency of choice.

The vibration frequency can be controlled by varying the electromagnetic excitation frequency. The resonance frequencies of intact and fractured struts center around 7.5 KHz and 2.2 KHz respectively [2]. The acoustic field generated by the vibrating strut can be measured and the frequency at which resonance occurs can be used to differentiate between an intact outlet strut (IOS) and an SLS valve. Thus the problem of fracture detection translates into a problem of measuring the frequency of the acoustic signal radiated by the strut.

SOLID MODEL

An exact 3D solid model of the heart valve was developed from the engineering diagrams for subsequent analysis. Unigraphics, a solid modeling package was used to develop the solid model of the BSCC heart valve. The Fig.4 show the various views of the developed solid model.

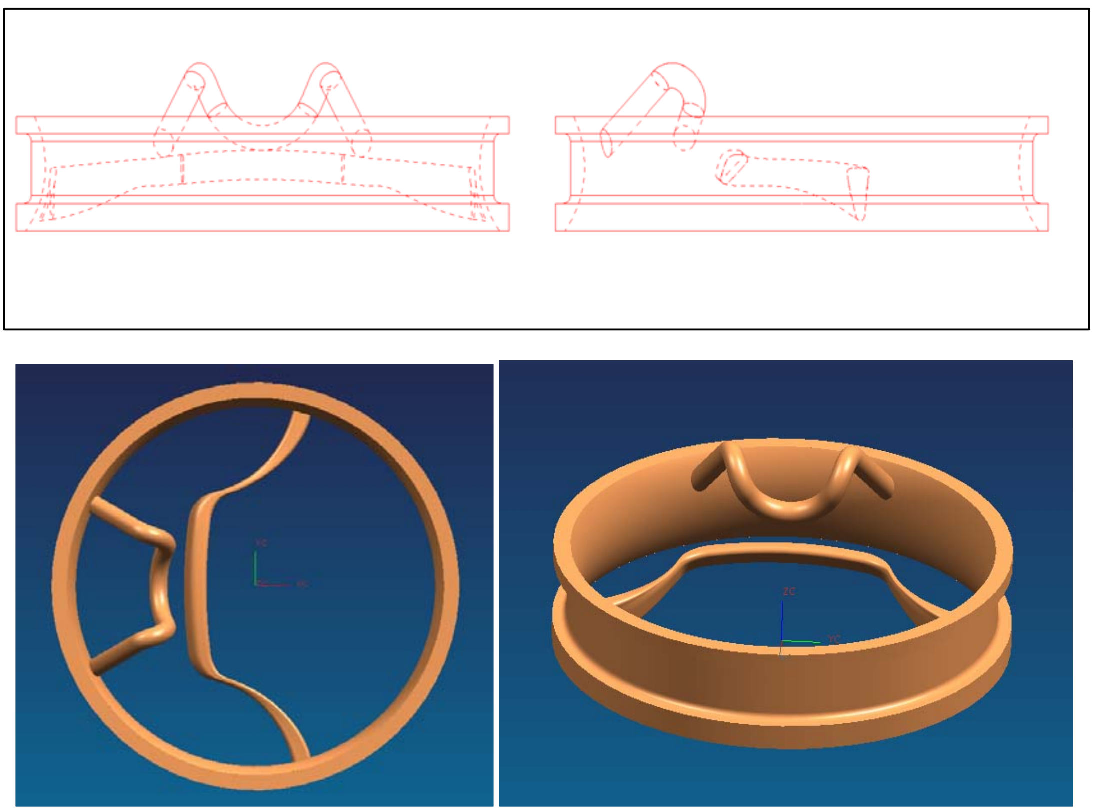


Figure 4 Solid Model

Finite Element Analysis

An approximate solid model was developed in ANSYS, a Finite Element Analysis software for faster analysis. The Model was meshed by using Tetrahedral elements. The Model was used to simulate the actual test conditions to find the various modes of vibration of the heart valve and their relative amplitudes of vibration.

Figure 5 FEM Mesh

Modal Analysis

A modal analysis of the valve was performed with 3 models (ring, ring with Inlet Strut and complete model). In the case of the complete model and the model with the inlet strut alone there are local modes of vibration of the struts alone. The main mode of vibration is rotation along the symmetry axis as shown in Fig. 6.

MODE	MODE TYPE	FREQUENCY (Hz)		
		Ring	Inlet Strut	Complete
1	Rotational	0.04	0.03	0.03
2	Cantilever	404.70	403.15	403.12
3	**Z Axis**	**893.67**	**876.34**	**891.05**
4	Local Mode of Outlet Strut	-	-	2616.80
5	Expansion	2937.30	2930.40	2957.70
6	Local Mode of Inlet Strut	-	4102.40	4107.20

HARMONIC ANALYSIS OF VALVE

A harmonic analysis is defined as the response of the valve as the frequency of a sinusoidal force varies. If the force applied is given by $F_o\sin(\omega t)$, the displacement of a particular node is plotted as a function of ω. This gives the relative displacements of the body at various frequencies and also helps in identifying the main modes of vibration.

The confirmation of the prominent mode is provided by the harmonic analysis of the ring. The Fig. 6 shows a high value of displacement at around 890 Hz which makes it the most prominent mode.

One of the results verified was the effect of changing the orientation of the measuring point in the valve. As expected the displacements were maximum when the measuring point was perpendicular to the symmetry axis (X axis) of the valve and less if measured on the axis. This is because the axis of the main mode of vibration coincides with the X axis.

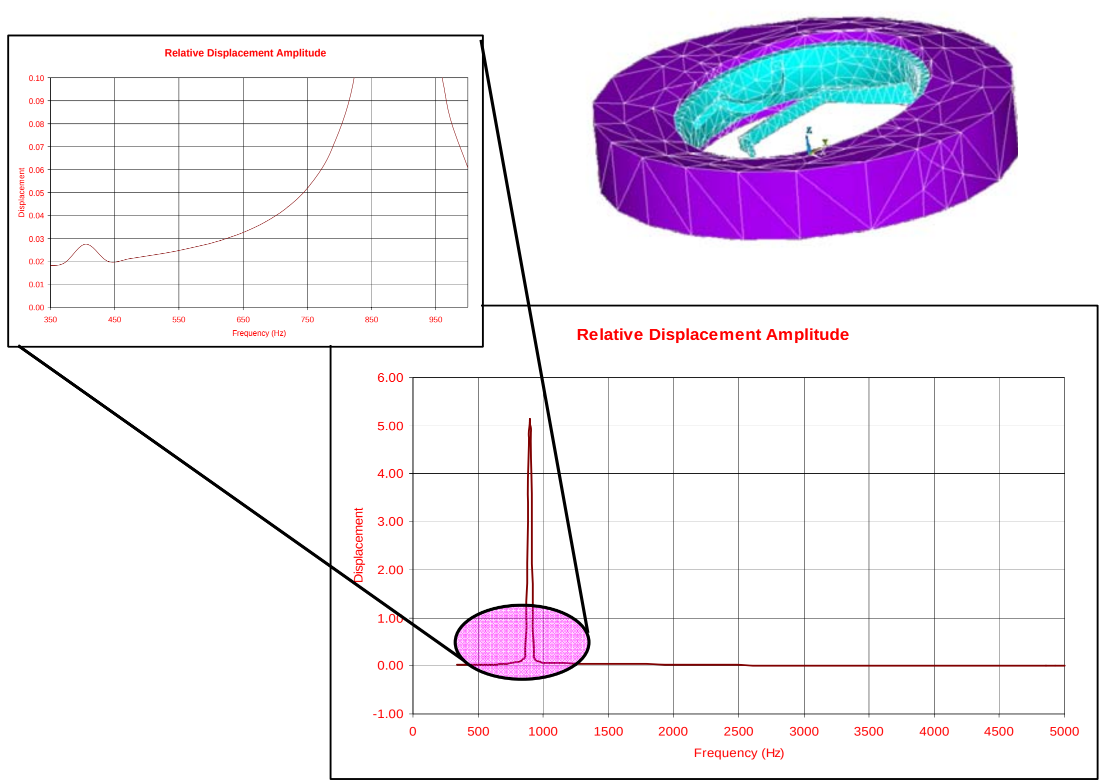
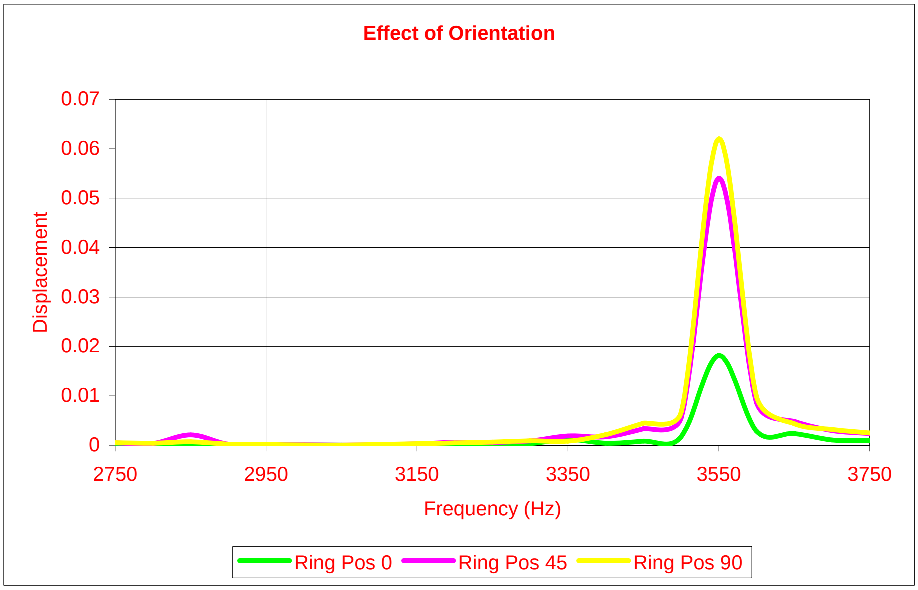


Figure 6 Prominent Vibration Mode



COMPARISON OF SLS AND IOS VALVE

A SLS valve model was prepared by removing some material from one of the legs of the outlet strut. A gap of width 2 mm was used to simulate the SLS condition as shown in Fig. 7.

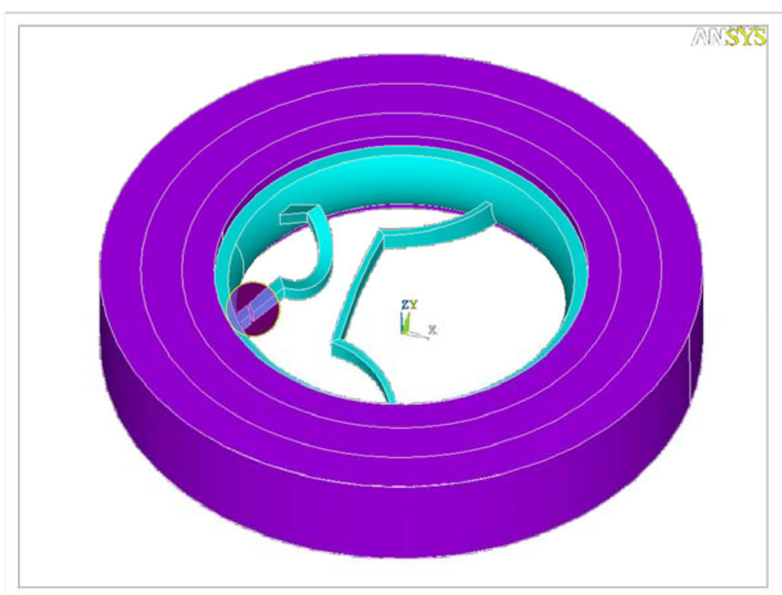


Figure 7 SLS Valve

A harmonic analysis was performed in the frequency ranges 2500-4000 Hz and 5000-6500 Hz (Fig. 11). The SLS valve showed a peak at around 2800 Hz and 3550 Hz. On the other hand the IOS valve displacement peaked at around 6000 Hz which was not present in the case of the SLS valve. This is almost in accordance with the theoretical predictions [2] but the exact values differ. This may be due to the variation in the values of material constants used for the suture ring. It can be corrected by modeling the suture ring as a viscoelastic material having the properties of human tissue.

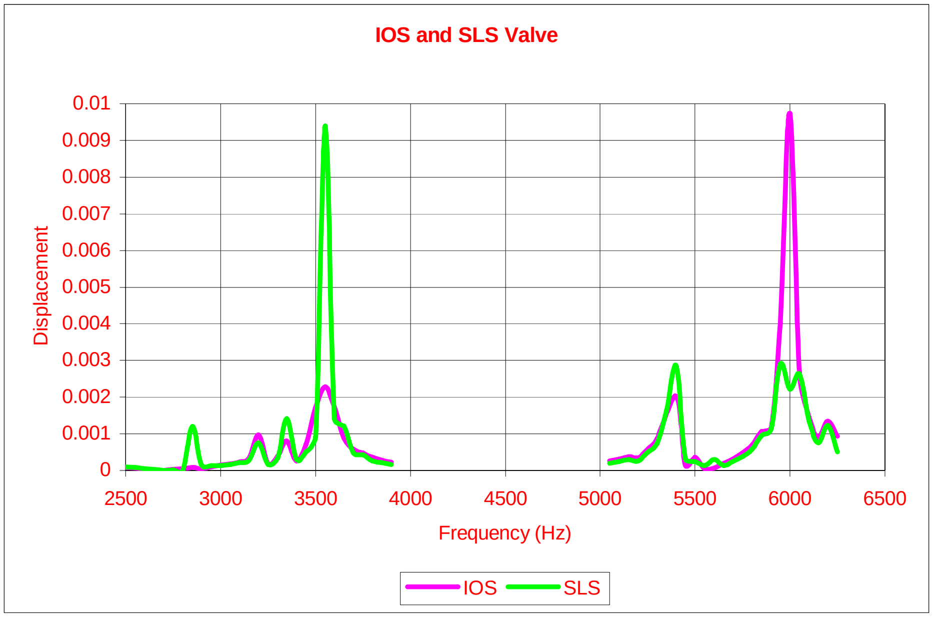


Figure 8 Comparison

REFERENCES

1. T.D. Plemons, M. Hovenga, H. Reeder and J. J. Dow, "*Classification Of Bjork-Shiley Convexo-Concave Valve Status By Detection Of The Intact Outlet Strut Resonant Frequency*", Proc. of the 15th Annual International Conference of the IEEE, pp. 389 –390, 1993.

2. S. Udpa, "*New Electromagnetic Methods For The Evaluation Of Prosthetic Heart Valves*", Journal of Applied Physics, Vol. 91, No. 10, pp.1-5, 2002.