Proceedings of the ASME 2009 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2009
August 30 - September 2, 2009, San Diego, California, USA

DETC2009-87830

# NATURAL FREQUENCIES OF COMPOSITE CYLINDRICAL HELICAL SPRINGS MANUFACTURED USING FILAMENT WINDING

**Erol Sancaktar and Sunil Gowrishankar**

**Department of Polymer Engineering**

**The University of Akron**

**Akron, OH 44325-0301, U.S.A.**

## ABSTRACT

We devised a novel technique to fabricate composite cylindrical helical springs using glass, and carbon fibers and in hybrid form, embedded in a matrix of epoxy resin, thus introducing a novel approach to spring making by incorporating the versatility of the filament winder. Our method allows us to vary the dimensions of the spring with considerable ease. This is accomplished in three stages. The first stage involves the proper selection of the resin and hardener. In the next stage, the glass and carbon fibers are completely soaked in a resin bath and encased in PVC tubing of three different inner diameters, which determine the wire diameter of the composite spring. Using a filament winding technique, these fiber filled tubes are wound on PVC mandrels of three different diameters. The natural frequencies of the manufactured composite springs were measured experimentally to study the influence of dimensional parameters, i.e., diameter ratios (D/d) and number of active turns (N = 6 and 7) on the free vibration frequencies. The natural frequencies for glass and carbon fiber and hybrid springs were measured using an MTS fatigue tester, and the resonance of the springs were captured using a digital camera.

## 1. INTRODUCTION

Helical Springs continue to draw the attention of several researchers around the globe with continuing efforts to optimize their various properties including weight, vibrational properties and durability. Most of the work done over the last century focused on the use of metal alloys towards fabricating helical springs. Even though, the developments in alloying techniques have come a long way, the continuing quest for improved performance such as low weight, high strength and durability as well as the ability to predetermine performance characteristics precisely has not been fully accomplished.

The last four decades witnessed a dramatic increase in the production of composites and this could be attributed to the very high strength-to weight, and stiffness-to weight ratios possessed by them. Higher specific strength in composites led to the reduction in weight in many mechanical components. This is a very important factor in moving components, especially in the transportation industry, where reduction in weight results in greater efficiency leading to reduction in costs. For example, the use of composite leaf springs has been reported in the literature for light-weight vehicle applications [1]. Boeing Inc. has taken this beneficial aspect of helical composite springs for the design of louvered doors, which are used on their 757 and 767 aircraft. It has been estimated that the weight savings achieved through the use of composites amounted to about 1000 kg over conventional metallic structures [2].

The method of fabricating the helical composite springs has a major influence on their final properties. Traditionally, composite springs have been made by impregnating glass/carbon fibers in a suitable resin. The wet fibers were then carefully wrapped around using a water-soluble tape such as Poly Vinyl Alcohol (PVA).

These wrapped fibers were wound around a grooved metal mandrel, and cured at elevated temperatures. The wrapping tape can be removed by soaking the final product in water [3]. Since this process is tedious and labor intensive, an alternative is proposed herein which makes use of the filament winding technique. We reported on the stiffness and nonlinear mechanical behavior of composite helical springs we manufactured using the same technique in our earlier publications [4, 5].

The primary objectives of the present study was to experimentally investigate the effects of number of active coils, ratio of diameters of maximum cylinder to the diameter of the wire and material types on the fundamental natural frequencies of helical springs with circular cross sections by using an MTS fatigue testing machine.

## 2. EXPERIMENTAL

Our novel procedure involves encasing the impregnated fibers in a flexible PVC tube. These continuous strands of impregnated fibers are then wound on to a mandrel. Using a computer-controlled system, the impregnated fibers are precisely laid down at a specific angle and at a specific pitch. The material is allowed to cure overnight and the PVC tube is then peeled off leaving behind the fabricated spring. This method is not limited to single fiber reinforcement, and hybrid springs composed of two or more varieties of fibers can also be fabricated. Thus, incorporating a mixture of glass and carbon fibers into a polymer matrix gives a relatively inexpensive composite, owing to the low cost of glass fibers, with mechanical properties enhanced by the excellent stiffness of carbon.

### 2.2 Glass and Carbon Fibers

Glass and carbon fiber constituents were used in this study. The glass fibers were 366 High TEX Type 30 manufactured by Owens Corning (Toledo, OH). This high strength E glass fiber of 10μm diameter was supplied as a continuous roving. The 366 High Tex Type has low weight density (104 meters per kilogram) as well as excellent and fast wet out ability with epoxy resins. Some of the properties of 366 High Tex type glass fibers are given in Table 1.

Table 1. Properties of E glass (366 High Tex Type) fibers

| | |
|---|---|
| Young's Modulus@23°C: | 72.3 GPa |
| Tensile Strength @23°C: | 3.445 GPa |
| Density: | 2.58 gm/cc |
| Refractive Index: | 1.558 |
| Elongation: | 4.8 % |
| Softening Point: | 846° C |

The carbon fiber chosen for our experiments was 7.2μm diameter PANEX® 33 continuous fibers manufactured from Polyacrylonitrile (PAN) precursor. The fibers provided by Zoltek Corporation (St. Louis, MO) had large filament count strands, which permit fast and efficient build up of carbon fiber reinforced composite structures. These fibers are also highly compatible with epoxy and phenolic resins and give excellent wettability. The key properties of PANEX® 33 carbon fibers are given in Table 2.

Table 2. Properties of PANEX® 33 carbon fibers

| | |
|---|---|
| Young's Modulus@23°C: | 228 GPa |
| Tensile Strength @23°C: | 3.80 GPa |
| Density: | 1.81 gm/cc |
| Electrical Resistivity: | 0.00172 ohm-cm |
| Carbon Content: | 94 % |
| Yield: | 278 m/kg |

### 2.3 Epoxy and Hardener

The Shell Epon 815C® resin (Shell Chemicals, CT) used in our work is a low viscosity liquid bisphenol A based epoxy resin containing n-butyl glycidyl ether. The epoxide equivalent weight of Epon 815C is reported by the manufacturer to vary between 180-195, and its viscosity to range from 5-7 poise. The hardener used was a liquid polyamine, DETA (Diethylenetriamine), manufactured by Shell Chemicals. DETA was selected because of its excellent compatibility with epoxy resins for fast and room temperature cures, providing good resin properties at room temperature (and below 82ºC, the minimum heat distortion temperature reported by the manufacturer).

Table 3. Properties of Epon 815C Resin

| | |
|---|---|
| Epoxide Equivalent Weight: | 180-195 |
| Viscosity @25°C: | 5- 7 poise |
| Density @25°C: | 1.15 gm/cc |
| Flash Point: | 74°C |
| Color, Gardner: | 1 max |

The cure conditions used were 38°C for 12 hours with 12wt% DETA.

### 2.4 Filament Winder

The filament winding machine (Composite Machines Company, Salt lake city, UT) was the primary production equipment used in our study. It is a 4-axes controlled machine (CMC) equipped with a 2-speed gearbox, which is capable of generating speeds between 10 and 250 rpm. The horizontal and radial movement of the carriage, the rotating eye and the motion of the spindle (clockwise and anti-clockwise direction) constitute the four axes through which the filament winder can function.

For our study, helical springs of three different coil and wire diameters were required. This was accomplished with the use of 3 different PVC pipes of outside diameters, 37.05 mm, 42.5 mm and 48.45 mm, for which tubing of 3.175 mm, 4.7625 mm and 6.35 mm inside diameters were selected to form the spring wire diameter. Using an Xacto knife, a clean incision was made on the PVC tube. Care was taken to ensure that the incision was along a straight line, which would otherwise leave a poor surface finish on the spring wire.

The procedure for the fabrication of helical springs can be broken down into three stages. First, the number of glass/carbon fiber strands that could be accommodated within the tubing had to be determined. This was done by measuring the cross sectional thickness of a strand of fiber using a micrometer and comparing it with the inner diameter of the tubing into which it is to be enclosed. This gave us an idea of the number of strands that were required to fill the PVC tube completely. While a decision on the approximate number of strands was being made, the reduction in diameter due to wetting by the epoxy was also taken into consideration. The fibers were then attached to specially made chucks. These chucks were made using cylindrical wooden bars into which a hole was drilled along its length. Metal roller bearings were fixed on the ends of the chucks. One of the chucks was attached to the headstock (moving) and the other to the tailstock (stationary) of the filament winder.

The second stage involved preparation of the epoxy resin bath, which was done by mixing together 88 grams of Epon 815-C and 12 grams of DETA using a mechanical stirrer. This mixture was poured into a wide base aluminum pan. Subsequently, the fibers were immersed in the thermosetting resin solution and wetted thoroughly. These wetted fibers were then mounted back on to the winder and twisted either in the clockwise or anticlockwise direction. Care was taken to see that the direction in which fibers were rotated was kept the same throughout our study. In all our experiments, fibers were twisted in the clockwise direction, which results in a tightening action on spring with respect to the direction which they are employed, and were wound in counterclockwise direction and loaded in compression.

It was observed that after 28-30 rotations, the fibers were twisted taught enough that the tailstock began to rotate. It was at this point that further twisting was discontinued. In order to maintain a homogeneous fabrication technique, the number of rotations the fibers were subjected to, was limited to 30. The slit PVC tube was then carefully slid on to the twisted fibers. At this stage, the fibers were further subjected to an additional five turns, which helped squeeze out the excess resin and compact the fiber bundle, thus imparting a cylindrical shape to the fibers.

In the third stage, the PVC pipe of a specific diameter (say 37.05mm) was mounted on to the winder. The diameter of the pipe determines the coil diameter of the spring to be manufactured. In order to facilitate easy removal of the cured spring, the mandrel was sprayed with a mold release agent. Special software that was solely created for winding helical springs was used to wrap the fiber bundle around the mandrel at a precise winding angle and at a predetermined pitch. It is essential to make sure that the coils of the spring be wound in a direction opposite to the strand direction. This not only ensures the binding between strands but also the unwinding action that may be caused due to a twisting moment can be avoided when the spring is loaded in the compressive mode. Since our study was focused on the evaluation of stiffness variation for springs of a fixed helix angle, the winding angle for all springs was set to 80º, which yielded a helix angle of 10º. The ends of the wound springs were fastened by an adhesive tape or clamped using binder clips. Care was taken to ensure that the ends of the springs were as flat as possible (helical angle = 0°). This facilitated the subsequent experiments involving the determination of stiffness and resonance measurements.

The specimens were allowed to cure at 30º C and 35% relative humidity for over 12 hours. After complete curing, the PVC tubing was carefully peeled off leaving behind the fabricated spring. The above procedure was repeated with two other mandrels of diameters 42.5 mm and 48.45 mm. In order to make helical springs of varying wire diameters, PVC tubes of differing inner diameters were used. When larger diameter tubing was used, the number of strands of glass/carbon fibers had to be increased altering the stiffness of the spring. The required number of strands to fill the appropriate PVC tubing completely is illustrated in Table 4.

Table 4. Number of glass/carbon fiber strands used

| PVC tube (I.D.) mm | Glass Fiber Stands | Carbon Fiber Strands |
|---|---|---|
| 3.175 | 10 | 2.5 |
| 4.762 | 22 | 5 |
| 6.35 | 30 | 8 |

The same procedure was followed in order to make hybrid springs with glass and carbon fibers combined. For this purpose, the ratio of volume fractions of carbon to glass fiber strands had to be determined first. It was observed that the volume occupied by one strand of carbon fiber was approximately equivalent to that occupied by 4 strands of glass fibers. The combination of glass and carbon fibers that was used in the making of hybrid springs is depicted in Table 5.

## 2.5 Determination of Natural (Resonant) Frequency

Measurement of the natural frequencies of various helical springs that had been fabricated using the method

Table 5. Combination of fibers used for Hybrid Springs

| PVC Tube (I.D.) mm | Combination of Fibers |
|---|---|
| 3.175 | 6 strands Glass Fiber<br>+ 1 strand Carbon Fiber |
| 4.762 | 12 strands Glass Fiber<br>+ 2strands Carbon Fiber |
| 6.35 | 18 strands Glass Fiber<br>+ 3strands Carbon Fiber |

described above was done using an MTS fatigue tester. A special clamping attachment to which one end of the spring could be fixed was devised using two-L shaped metal plates. These plates were fastened to each other using a metal strip that was placed diagonally across the surface and was bolted to either plate. The end coil of the spring, which was made to be flat, was secured under this metal strip. The entire assembly of the spring with the clamp was attached to the lower grip of the MTS testing machine and the upper end was left free. In this experiment, the specimen was made to undergo a harmonic motion by the application of a sinusoidal force to the lower clamp. A frequency level, at which the spring was expected to resonate, was selected and the amplitude was increased until resonance could be visually observed. A chart recorder was connected to the MTS machine for the purpose of recording the number of cycles that the spring was subjected to in a specific time. This allowed us to calculate the actual frequency at which the spring was vibrating. Since the resonance of the spring was clearly visible to the naked eye, it was deemed not necessary to make use of strain gauges to observe it. Since the machine was not capable to produce frequencies less than 16 Hz or greater than 90 Hz, all the possible natural resonant frequencies could not be identified. Making use of a Nikon digital camera, the vibration patterns were photographed.

The above procedure was repeated for carbon, glass and hybrid springs to study the effects of changing the coil diameter, wire diameter and the number of active turns on the natural frequencies of helical composite springs under free vibration conditions. A composite helical spring made with glass strands and the same spring at its 28.25 Hz resonant frequency are shown in Figure 1.

## RESULTS AND DISCUSSION

Our analysis and design efforts for composite helical springs included the determination of the first four natural frequencies of helical composite springs experimentally. The experimental program was executed for carbon fiber, glass fiber and hybrid springs having turns N = 6 and 7, and for different coil/wire diameters to establish the influence of these variables on the natural frequencies. Our findings revealed the following:

In the case of glass springs with 3.70 mm wire diameter, the natural frequencies are strongly affected by the D/d ratio. As we change the D/d ratio from 10.02 to11.39 and further to 14.36, we notice a significant decrease in the natural frequency values from 28.25 Hz to 21.31 Hz (approximately 24.56%) and further down to 14.90 Hz (approximately 47.26%). Thus varying the D/d ratio for these helical springs can exert a fairly linear but strong influence. Another observation is the relative closeness of the second and third modes indicating coupled modes of vibration (Figure 2). Identical results are also observed when the number of active turns is decreased from N =7 to 6 (Figure 3).

Figure 1. A composite helical spring made with glass strands (left), and the same spring at its 28.25 Hz resonant frequency (right).

For the wire diameter d = 5.49 mm, we again notice the natural frequencies to decrease from 35.10 Hz to 27.99 Hz (20.25%) and to 19.36 Hz (44.8%) for a corresponding change in D/d ratio from 7.36 to 8.15, and to 9.97, thus confirming our predictions (Figures 4 and 5). The same trend is also observed for glass springs of a higher wire diameter, i.e., d = 7.21 mm (Figure 6).

Similar results are also observed in the case of the carbon fiber springs. A decrease in frequency from 28.73 Hz to 17.77 Hz (approximately 38.15%) is observed when the D/d ratio changes from 9.94 to 14.15 (Figure 7). For the wire diameter d =5.58 mm, the natural frequency decreases from 38.49 Hz to 22.62 Hz (41.23%) for a change in D/d ratio from 7.13 to 9.88, suggesting a very similar but slightly greater values compared to those of glass springs (Figure 8). Higher natural frequencies were expected for carbon springs on account of their higher modulus, which is nearly three-times that of glass fibers.

Similar trends were obtained with hybrid strand springs as shown in Figures 9 and 10.

As observed from Figures 2-5, increases in the number of turns (N) result in lower values for the natural frequency. This effect is illustrated in Figure 11 using glass fiber springs with D/d = 8.15.

## CONCLUSIONS

We devised a novel method for the manufacture of helical composite springs using the filament winding technique, which is not only cost effective but also more versatile. We, then, experimentally investigated the effects of number of active coils, ratio of diameters of maximum cylinder to the diameter of the wire and material types on the fundamental natural frequencies of helical springs with circular cross sections by using an MTS fatigue testing machine. Our experimental results revealed that the natural frequency of composite helical springs can be lowered by increasing the coil diameter, in turn increasing the D/d ratio, and also by increasing the number of turns.

## REFERENCES

1. Sancaktar, E., Gratton, M., 1999, “Design, Analysis, and Optimization of Composite Leaf Springs for Light Vehicle Applications” Composite Structures 44, pp. 195-204.
2. Chawla, K.K., 1987, Composite Materials Science and Engineering, Springer-Verlag Inc., Chapter 8, pp. 159 – 163.
3. Hashimoto, K., 1984, Fiber Reinforced Resin Coil Spring and Method of Manufacturing the Same, U.S Patent No. 4,473,217.
4. Sancaktar, E. and Gowrishankar, S., 2002, “Design and Testing of Composite Cylindrical Helical Springs” Durability Analysis of Composite Systems, Y. Miyano, A. H. Cardon, K. L. Reifsnider, H. Fukuda and S. Ogihara (Eds.), pp. 361-367, A. A. Balkema Publishers, Lisse, The Netherlands.
5. Sancaktar, E. and Gowrishankar, S., 2002, “Apparent Nonlinearities in Mechanical Behavior of Epoxy Based Composite Helical Springs” Proceedings of 2nd Canadian Conference on Nonlinear Solid Mechanics, E. M. Croitoiro (Ed.), The Pacific Institute for the Mathematical Sciences, pp. 291-302.

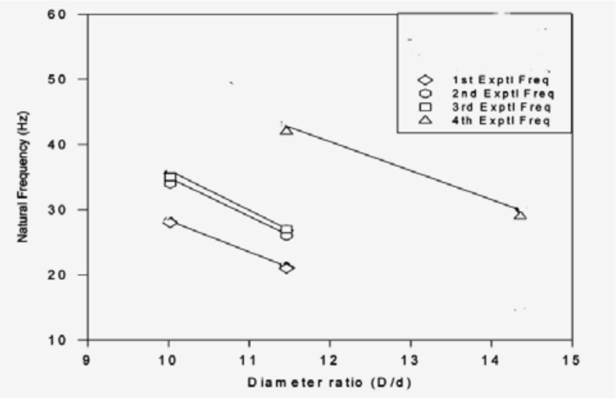

Figure 2. Variation of Natural Frequencies with D/d Ratio for Glass Fiber Spring (d = 3.70mm, N = 7).

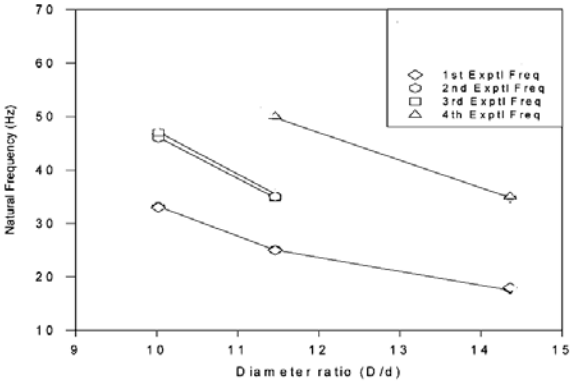

Figure 3. Variation of Natural Frequencies with D/d Ratio for Glass Fiber Spring (d = 3.70mm, N = 6).

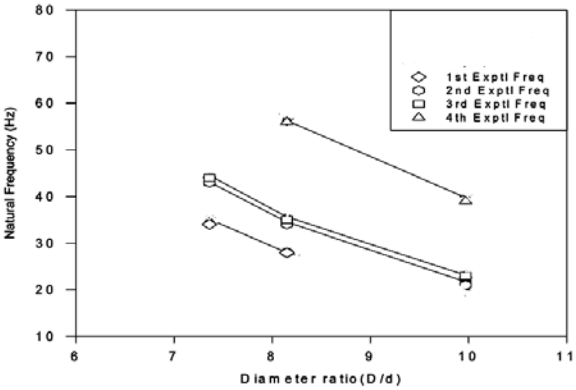

Figure 4. Variation of Natural Frequencies with D/d Ratio for Glass Fiber Spring (d = 5.49 mm, N = 7).

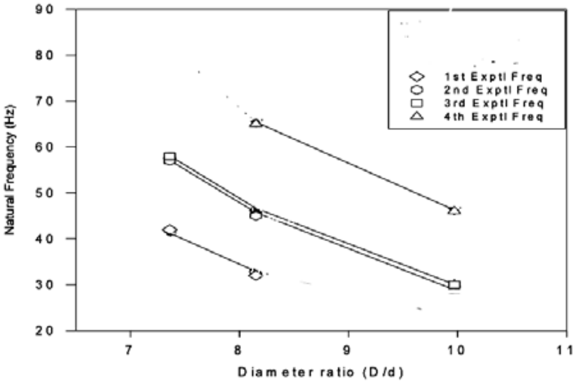

Figure 5. Variation of Natural Frequencies with D/d Ratio For Glass Fiber Spring (d = 5.49mm, N = 6).

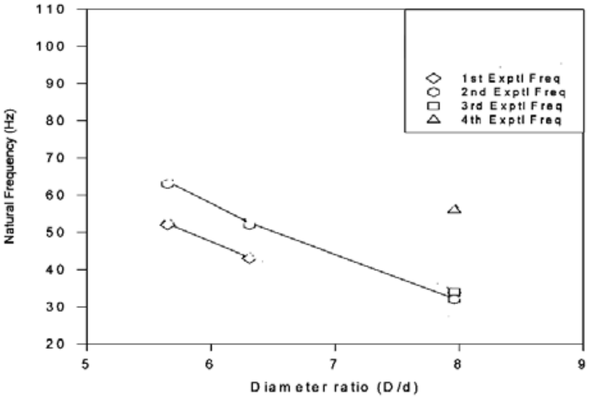

Figure 6. Variation of Natural Frequencies with D/d Ratio For Glass Fiber Spring (d = 7.21mm, N = 6).

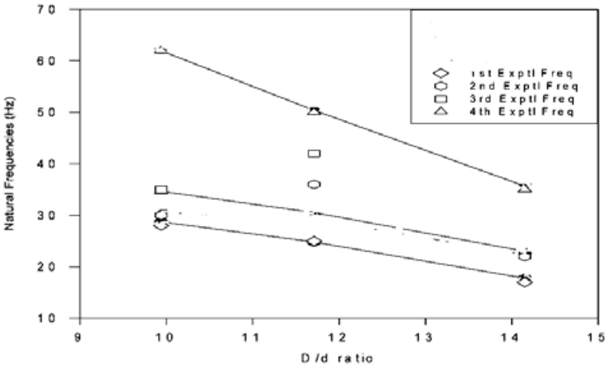

Figure 7. Variation of Natural Frequencies with D/d Ratio for Carbon Fiber Spring (d = 3.63mm, N = 7).

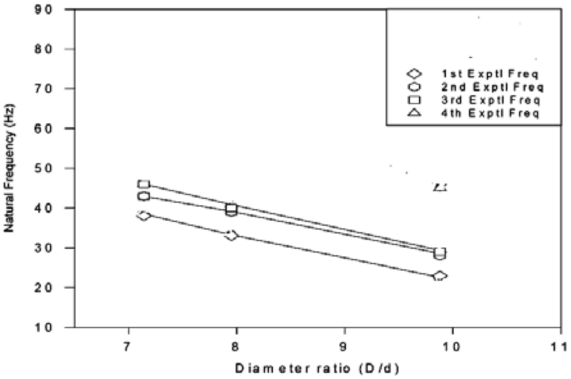

Figure 8. Variation of Natural Frequencies with D/d Ratio for Carbon Fiber springs (d =5.58mm, N=7).

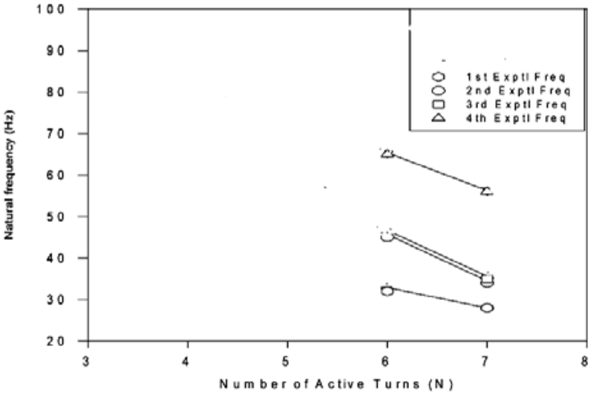

Figure 9. Variation of Natural Frequencies with Number of Turns for Glass Fiber Spring having D/d Ratio = 8.15.

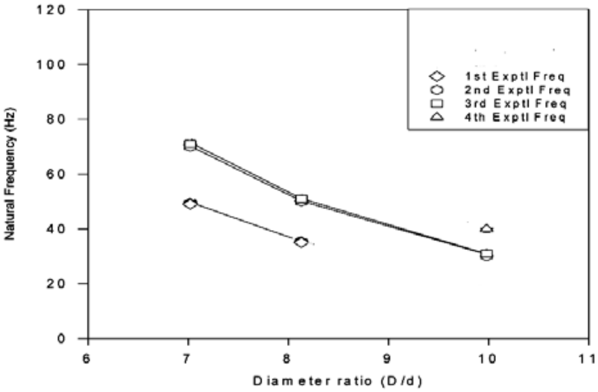

Figure 10. Variation of Natural Frequencies with D/d Ratio for Hybrid Spring (d = 5.52 mm, N =6).

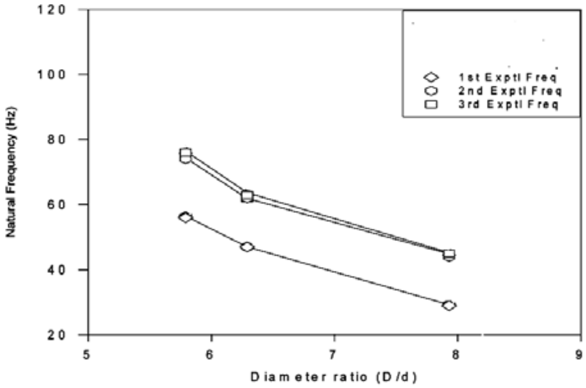

Figure 11. Variation of Natural Frequencies with D/d Ratio for Hybrid Spring (d = 7.20 mm, N =6).