Parametric Design and Comparative Analysis of a Special Purpose Flexure Spring

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Abstract. Flexure springs play pivotal role to ensure reliability and durability of the cryocooler compressors. The critical application of flexure spring intends to eliminate the wear, frictional losses and significantly vibrations. A parameter study was performed considering the design variables of a flexure spring to meet the requirements of the cryocooler compressors viz. complexity of the geometric configuration, radial and axial stiffness, fatigue life, material, etc. The parametric design approach was deployed using finite element analysis (FEA), to validate the same by experimental data to analyse the performance of the flexure spring. This paper also presents a comparative analysis of the design variables in terms of axial and radial stiffness, induced stress as well as the manufacturing methods' considerations to optimize the design of a special purpose flexure spring for the cryocooler compressors. Furthermore, experimental study of the flexure spring was carried out in order to maximize the stroke.

1 Introduction

Cryocooler originates from the phrase cryogenic cooler which provides active cooling down to cryogenic temperatures. Cryocoolers finds versatile applicability across pulse tube, Stirling, GM, Joule Thompson industrial applications, etc. The wide applications are discussed in the following table 1:

Table 1. The wide applications

Domain of applications	Applications of Cryocoolers
Space missions	Observing in the infrared, gamma-ray and x-ray spectrums, Satellite imaging
Police and Security	Infrared sensors for night vision goggles; surveillance
Defense	Infrared sensors for missile guiding control used in tactical applications; satellite based Infrared sensors assisting surveillance and monitoring
Commercial	Used in Cryopumps for semiconductor manufacturing and fabrication; High temperature superconductors for telecom applications; Semiconductors for high speed computing devices; Programmable Focusing Mechanism
Medical	Cooling magnets for MRI scanning systems; SQUID magnetometers for heart and neural studies; Liquefaction of oxygen for warehouse storage at hospitals; Cryogenic catheters and cryosurgery applications
Transportation & Logistics	LNG integration for fleet vehicles; Super conducting magnets in maglev trains/metros
Energy Supplies	Liquified Nitrogen for storing surplus energy; Infrared sensors for thermal loss detection; Super Conducting magnetic energy storage for peak shaving and power reconditioning; power applications (motors, transformers, etc.)
Agriculture and Biology	Storage of biological stems, cells and specimens for experimentation and research

Justifying the versatility of cryocoolers in general, the salient features are high resolution, high precision, high sensitivity, high power density, low power and low noise. The major concern for the applications of cryocoolers relies on the reliability for the development of tactical cryocoolers.

Cryocoolers requires high reliability in performance and high operating life. The linear motors are preferred over the rotary compressors because rotary compressors apply large radial forces and cause large amount of wear and also require lubrication. Lubrication is the common pain point in cryocoolers. For maintenance free operation, longer life for cryocoolers, a special purpose flexure spring is designed. The introduction of the Flexure spring technology enables more reliability. Flexure springs play pivotal role to ensure reliability and durability of the cryocooler compressors. The critical application of flexure spring intends to eliminate the wear, frictional losses and significantly vibrations. The flexure spring operates by bending of spiral arms.

The flexure spring boasts the following advantages:

- Simple and inexpensive.
- Compact, lightweight, low friction.
- Manufactured by Chemical itching, wire cut EDM, WJM.
- Long life and highly reliable.
- Noiseless during operation.

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Fig. 1 A special purpose flexure spring

Fig.1 shows the special purpose flexure spring.
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2 Research Motivation

A flexure spring mostly relies on the material which can be repeatedly flexed without disintegrating; so, the selection of the material becomes critical for the same. Most of the metals will tend to experience fatigue with repeated flexing, and will ultimately snap. Another point for selection of Flexure springs revolves around very low but uniform friction.

The essence of special type flexure spring lies in the fact that it acts a spring in axial direction (exhibiting low stiffness) and it acts as a bearing in radial direction (exhibiting high stiffness).
The parametric study was conducted to meet life requirements of cryocooler compressors especially for space applications. The parameter study approach was deployed to identify the optimum geometrical configuration; and it was achieved through the CAE package and validated through the experimental results.
As mentioned, the preferable way to achieve high operating life and reliability is by refraining physical contact between the piston and cylinder encompassed in the compressor. The supporting piston mass at the front and back side with high radial stiffness using flexure springs would be the most competent way to accomplish the same.

3 Literature Survey

The very concept of a flexure spring was put forward by A. Wolf et al. in 1938 and later granted with the patent for it [1]. The application was intended for capturing the Earth's Vibrations using mounting in a vibration detector. University of Oxford, late in 1981, had employed flexure springs in a Stirling cryocooler first time for the research purpose [2]. In 1992, Using Finite Element Method, the analysis was carried out by Wong et al. and proposed optimization of a three spiral flexure bearing. The same was validated with the experimentation. The researchers found that the radial stiffness of flexure bearing gets decreased with axial displacement and the maximum stresses get induced at the spiral cut ending [3].
Marquardt et al. presented that the ratio of radial to axial stiffness of the flexure spring could be considered to choose the appropriate geometrical configuration in correlation to the design parameters for flexure bearings [4].
The correlation was further insisted and presented by Wong et al.to provide the conclusion on static and dynamic testing using Finite Element Method for a three spiral cut flexure geometry. The results were validated through experimentation and concluded that the dynamic stresses should be considered for the fatigue analysis [5].
Analysis of a three-spiral flexure spring by Finite Element Analysis approach was done by Gaunekar et al. and proposed that axial displacement leads to increase in the stresses. Also, they pointed out that the axial stiffness and radial stiffness of the geometry illustrated a linear behaviour when plotted against the axial displacement of the spring. The researchers had developed normalised graphs for three parameters

1. Maximum stress,
2. Radial stiffness and
3. Axial stiffness with normalized axial displacement.

The findings were validated using experimentation with a fibre–optic interferometer technique and a simple dead weight methodology. The major findings were that the axial and radial stiffness of the flexure geometry is directly proportional to spring material thickness, which resulted in normalised graphs which would be stepping stone for the flexure bearing design considerations and optimization [6].
Z. S. Al-Otaibi and A. G. Jack considered a flexure bearing design for a linear motor supported with experimental investigation and validation of the results. The research carried out projected that an increase in spiral angle decreases the stresses and thereby axial stiffness of the disc, while the axial stiffness increases with the thickness of the flexure geometry [8]. These research outputs were also later reinforced by C.J. Simcock et.al who performed iterations using strain gauges and studied a flexure spring to identify bearing stresses [9].
Recently, Amit Jomde et al. had analysed the various parameters to find equivalent stress and stiffness for beryllium copper UNSC 17200 material. the researchers considered the parameters focusing on performance and service life at lower operating stresses and higher stiffness for the given application [10].
Yingxia et al. had proposed finite element simulation for the spring grooved with spiral slits under deformation. The research findings were carried out for the deformation

pattern, the stress distribution, and the natural frequency of the flexure spring with three spiral slots [11].
The performance of Oxford and triangle flexure bearings were investigated by Wenjie Zhou et al. The researchers had put forward that the triangle arm flexure bearings were responsible for larger radial/axial stiffness ratio, and the size of linear compressors could be miniaturized considering the adequate parameters [12].

4 Methodology

This research work presents a comparative analysis of the design variables in terms of axial and radial stiffness, induced stresses considerations to optimize the design of a special purpose flexure spring for the cryocooler compressors. Furthermore, experimental study of the flexure spring was carried out in order to maximize the stroke of displacement.
This research investigation has considered the following design approach:

1. To achieve higher mechanical spring stiffness – compact size
2. To accomplish lower operating stresses and infinite fatigue life
3. To identify Optional material with better mechanical properties
4. To find best geometrical configuration

The most important design considerations for the special purpose flexure spring were:

- Fatigue Strength
- Radial Stiffness
- Axial Stiffness

Practically, a single unit of flexure spring disc would not perform and deliver the total desired stiffness. So, a stack of flexure springs was used in a parallel arrangement for the application. it means that multiple flexure springs were kept in parallel to achieve the desired stiffness. The total stiffness was the sum of individual discs arranged through the arrangement.

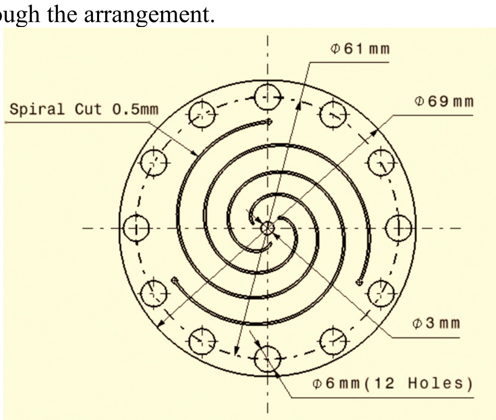

Fig. No. 2 Spiral flexure spring geometry

Figure 2 shows the spiral flexure spring geometry considered for the experimental investigation. Each flexure spring unit investigated had three spiral arms which would sustain the axial as well as radial loads. Each spiral arm traverses through an angle. The holes at periphery of the spring were provided to fix the disc rigidly for the experimentation purpose. To mitigate the misalignment in radial direction, the holes are slightly oversized with reference to bolt size for ease of mating components. The central hole was to allow shaft to get fitted. An abrupt change or discontinuity in spiral arm slit geometry leads to stress concentration. A material can fail potentially, via a propagating crack, when a concentrated stress exceeds the material's theoretical cohesive strength. Fatigue cracks always start at stress raisers, so removing such defects increases the fatigue strength. By drilling a hole at the end of the cut, the stress concentration may be reduced. The drilled hole, with its relatively large diameter, causes a smaller stress concentration than the sharp end of a cut.
The schematic illustration for an assembly of flexure springs is shown in Figure 3. The adequate numbers of flexure springs were stacked parallelly, in order to accomplish the intended axial and radial stiffnesses. During the experimental setup, the flexure springs were deflected through 5 mm stroke operating at the frequency of 50 Hz.

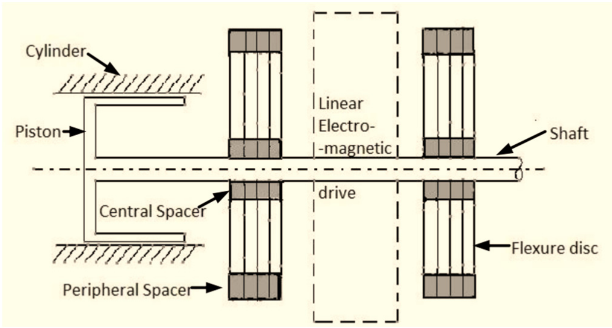

Fig. No. 3 Schematic Illustration of flexure spring assembly

Parametric considerations for FEA:

- Geometry of flexure spring
- Number of spiral arms
- Width of cut for the spiral/flexure arm
- Angle of traverse for spiral arms
- Disc thickness
- Effect of diameter of the spring
- Modification of the areas with higher stresses

Considering the above parameters individually, the exhaustive iterations through FEA were carried out. The geometry selected for the flexure spring was the spiral with helical arms. Then, the following materials were considered for the selection of the material for the flexure spring:

1. Stainless steel 301
2. Stainless steel 304
3. Cold drawn copper
4. Beryllium copper UNS C17000
5. Beryllium copper UNS C17200 (TH02)

So, it has been concluded to proceed with Beryllium copper UNS C17200 (TH02). It has been found that the material gives maximum stiffness.
For Finite Element Analysis, the following inputs were considered for further investigation:

- Thickness of flexure spring - 0.3 mm

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- Material for flexure spring – Beryllium Copper UNS C117200 (TH02)
- Axial displacement – 5 mm from mean position

Then FEA was carried out to find out the no. of spiral arms keeping above inputs in consideration.

The observations are depicted using the following Fig.4

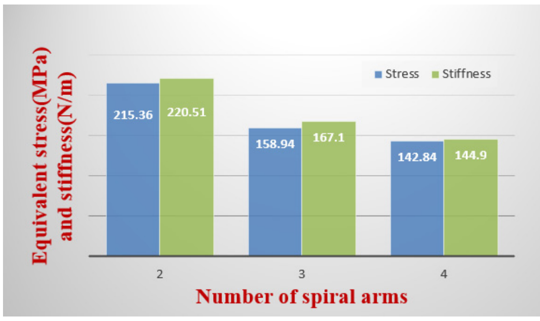

Fig. 4 No. of spiral arms vs eq. stress & stiffness

So, considering the best suitable results, three spiral geometry was finalized for the further investigation.
The finite element analysis for the selection of the width of spiral cut was done considering following options for the same:

1. 0.2 mm
2. 0.4 mm
3. 0.6 mm
4. 0.8 mm and
5. 1.0 mm

The observations recorded after doing analysis are illustrated in Fig 5

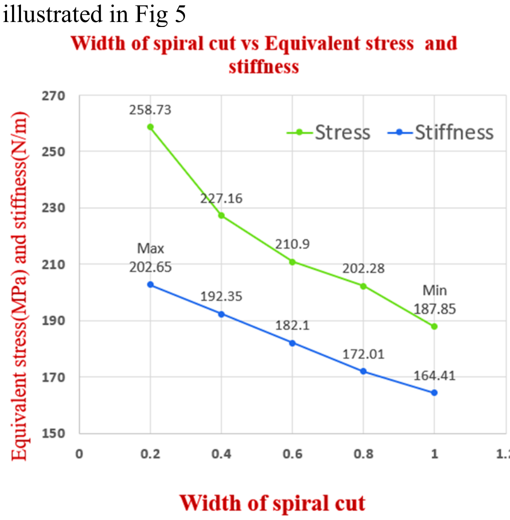

Fig. 5 Width of spiral cut vs Eq. Stress & Stiffness

From the results obtained, it has been concluded that as width of spiral cut goes on increasing, stiffness and equivalent stress both goes on decreasing gradually. For optimum design maximum stiffness and minimum stress is the prime criteria. If maximum stiffness is to be considered 0.2 mm spiral width is suitable and minimum stress is considered 1mm spiral width is suitable. Considering the design calculations, no. of flexure springs required would be more which is not acceptable.

The manufacturing for the flexure spring was considered by photochemical etching process and it would be difficult to get spiral cut less than 0.5 mm. So, taking the limitation in account, suitable width for spiral cut of 0.6mm has been taken.
For further analysis using FEA, the following inputs were considered for further investigation:

- Thickness of flexure spring - 0.3 mm
- Material for flexure spring – Beryllium Copper UNS C117200 (TH02)
- Axial displacement – 5 mm from mean position
- No. of spiral arms – 3
- Width of spiral cut – 0.6 mm

Then FEA was carried out to find out the spiral angle keeping above inputs in consideration. The following variations are considered:

1. 360°
2. 420°
3. 480°
4. 540°
5. 560° and
6. 570°

The observations are shown using the following Fig. 6

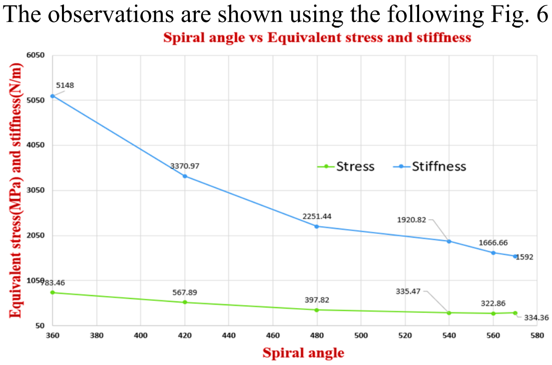

Fig. 6 Spiral Angle vs Eq. Stress & Stiffness

The results discussed in table 3 depicts that for 560° spiral angle minimum stress (322.86MPa) has been obtained and corresponding stiffness is 1666.66 N/m. So, spiral angle of 560° was selected for the further investigation.
The disc thickness as a variable parameter was considered later and the following variations were taken into account for optimum value:

1. 0.30 mm
2. 0.50 mm
3. 0.70 mm
4. 1.0 mm and
5. 1.25 mm

The following Fig. 7 shows the results for variation in disc thickness.

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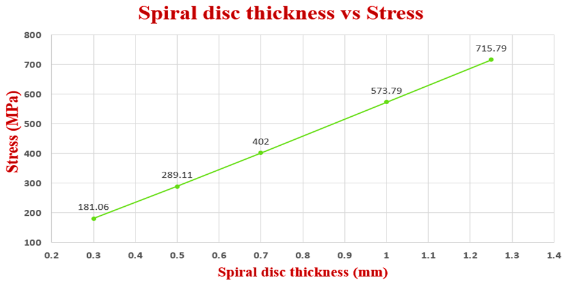

Fig. 7 Spiral disc thickness vs Stress

The stress induced in 1.00 mm and 1.25 mm thick material is more than its permissible limit, so 1.00 mm and 1.25 mm thickness are not suitable for flexure spring geometry. So, the simulation for deformation was carried out for 0.3 mm and 0.7 mm thick disc. It has been observed that, the stiffness value is more than 0.7 mm thick disc compared to 0.3 mm. And also, no. of disc units required for stacking was less in case of 0.7 mm. Hence, the value was considered for further evaluation.

5 Results and Discussion

The output from the parameter study carried out are as follows:

- Geometry of flexure spring – Spiral with helical arms
- Material selected - Beryllium copper UNS C17200 (TH02)
- Number of spiral arms - 3
- Width of cut for the spiral arm – 0.6 mm
- Angle of traverse for spiral arms - 560°
- Disc thickness – 0.7 mm

Table 2 Results and remarks

Parameter	Optimized value	Remarks
Flexure arm type	Spiral	Lowest stresses
Material	Heat treated Be-Cu (Yield = 1100 MPa)	High FOS
No. of spirals	3	Lower stress
Spiral Width of cut	0.6 mm	Manufacturing feasibility
Spiral angle	560^0	Low induced stresses
Disc thickness	0.7 mm	Max stiffness (FOS=2)
Disc Diameter	69 mm	For compact size

The above-mentioned parameters were evaluated against static stress and stiffness only. The flexure spring gets subjected to cyclic loading also. It becomes obligatory to verify whether these parameters are safe to fatigue loading. With reference to the above results, the value for stress was evaluated by comparing with S-N curve of the selected material.

The equivalent stress for 5 mm displacement and deformation was investigated, and the value was of 322.86 MPa. This stress later was used for finding out fatigue cycles by S-N curve to 10^8 cycles. The fig. 8 indicates the S-N curve for Be-Cu Alloy.

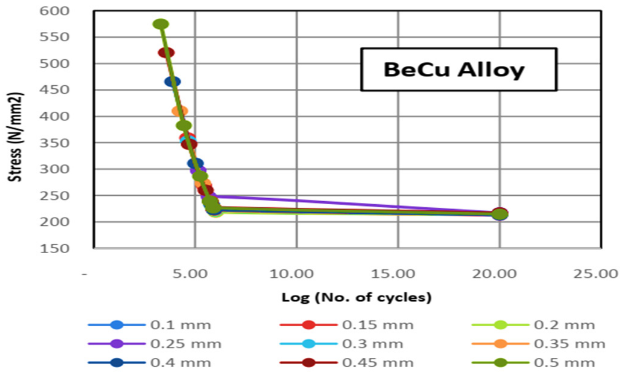

Fig. 8 S-N Curve of Be-Cu Alloy flexure spring

6 Result Validation using experimental set-up

The main objective of the parameter study was to optimize the design variables, geometric configuration, radial and axial stiffness, fatigue life, material, of a flexure spring. The endeavours have been taken in the research work to enhance the performance and improve upon the service life by achieving higher mechanical spring stiffness and lower operating stresses. As the flexure spring subjected to cyclic stress condition, the fatigue problem must be taken into consideration at the design stage in order to have flexure spring a long lifetime. Therefore, the validation of the parametric values achieved by FEA was critical and was carried out using three different set up namely:

1. Stiffness measurement test set-up.
2. Stress measurement test set-up.
3. Fatigue life test set-up.

The stiffness measurement was done using dead weights and dial gauge assembly. For the stress measurement, strain gauges were attached to the flexure spring surface. The surface was prepared with utmost care to ensure reliable bonding. And, the same had been integrated with multi-channel strain gauge data acquisition system for the better outputs in terms of strain value.

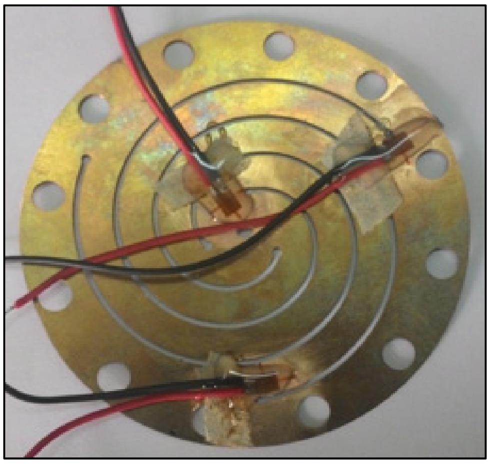

Fig. 9 Strain Gauge glued for readings

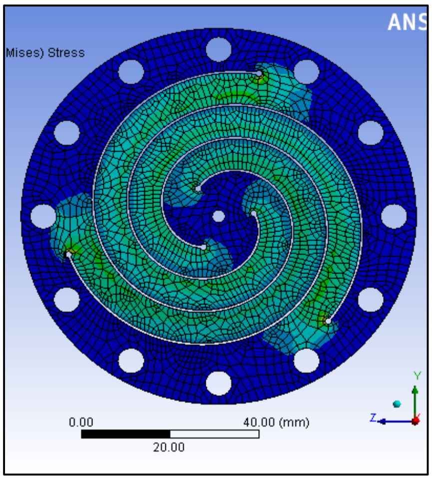

Fig. 10 Ansys image for the location fixing

The fatigue life setup had been fabricated considering the geometrical configurations for the flexure spring validation. The CAD model is shown in fig. 11 and actual setup in fig. 12

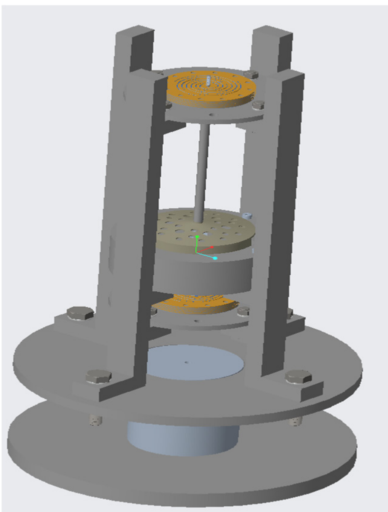

Fig. 11 CAD Model for fatigue life setup

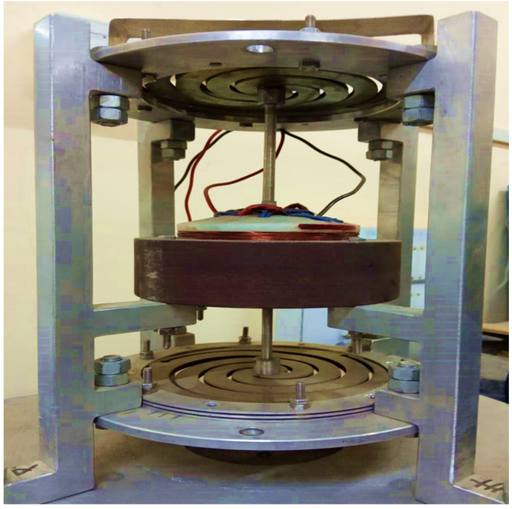

Fig. 12 Actual fatigue life setup

The fatigue life predicted by the S-N curve was compared with the experimental number of cycles undergone by the component before failure.

Table 3 Result Validation

Stiffness Validation		
FEA results (N/m)	Experimental results (N/m)	
1666	1729	
Stress validation		
Fix point	**FEA results (MPa)**	**Experimental results (MPa)**
A	**139.68**	**127.55**
B	**168.39**	**130.38**
C	**39.76**	**9.67**
Fatigue Life Validation		
FEA results (N/m)	**Experimental results (N/m)**	
10^8 cycles	10^8 cycles without failure	

7 Conclusion

The design variables and geometric configuration parameters for a flexure spring were varied using FEA in order to determine their influence on axial and radial stiffness, as well as on maximum occurring stresses. The parameter study approach presented in the research work can be referred for optimization of flexure springs different specifications.

The summary for the research findings is:

- The Parametric study using FEA was carried out for design optimization.
- The stresses, stiffness, and fatigue life (using S-N curve) were predicted by FEA.
- The results were validated by experimental setup for stiffness, stress & fatigue life.
- The natural frequency for the flexure spring decreases with the spiral angle and no. of spiral arms.

- The parametric design approach for the flexure springs seems compromising in nature when stiffness ratio and the maximum stresses need to be considered.

8 Future Scope

- The experimental investigation and validation for stiffness measurement has been going on.
- The fatigue life testing is being done with the modular arrangement for the different diameters of the flexure discs.
- The future objective of the work will be mainly to achieve the maximum stroke and to study non-linearity.
- The optional material with better mechanical properties for the flexure disc will be tried out for improvement in service life.
- Design approach will be optimized for different applications.

9 Applications

The versatility of flexure springs being a spring in axial direction and being a bearing in radial direction gives a cutting-edge advantage as far as applications are concerned. The applications of flexure springs are extensive in nature and can be found across following industries like:

- Space Technology
- Automotive Sector
- Energy Sector
- Medical & Diagnosis
- Machine tools Manufacturing
- Micro-manufacturing, MEMS and NEMS
- Electronics & Telcom sector
- Optics and Image capturing technology
- Pharmaceutical industries

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References

1. Wolf A. et al., (1938), Vibration Detector US Patent N. 2,130,213.
2. Davey, C., "The Oxford University Miniature Cryogenic Refrigerator", International Conference on Advanced infrared Detectors and Systems, London, (1981), 39.
3. Wong, T.E., Pan R.B. and Johnson A.L.,"Novel linear flexure bearing", in: Proc 7th Int. Cryo Conf, (1992), 675-698.
4. Marquardt, E., Radebaugh, R. and Kittel, P., "Design equations and scaling laws for linear compressors with flexure springs", in: Proc 7th Int Cryo Conf, (1992), 783-804.
5. Wong T.E., Pan R.B., Marten H.D., Sve C., Galvan L. and Wall T.S. "Spiral flexural bearing" in: Proc 8th Cryo Conf, (1995), 305-311.
6. Gaunekar A. S., Goddenhenrich T., Heiden C., "Finite element analysis and testing of flexure bearing elements", in: Cryogenics 36, (1996), 359–364.
7. Lee C. C. and Pan R. B., "Flexure bearing analysis procedures and design charts", in: Cryocoolers 9, Plenum Press, New York, (1997), 413-420.
8. Al-Otaibi Z. S., Jack A. G., "Spiral flexure springs in single phase linear-resonant motors", in: Proceeding of: 42nd International Universities Power Engineering Conference (UPEC2007), 184-187.
9. Simcock C. J., "Investigation of materials for long life, high reliability flexure bearing spring for Stirling Cryocooler Applications", in: Cryocoolers 14, (2007), 335-343.
10. Amit Jomde, A. Anderson, Virendra Bhojwani, Fayaz Kharadi, Suhas Deshmukh, Parametric analysis of flexure bearing for linear compressor., Science Direct, Material Today: Proceedings 4 (2017) 2478-2486.
11. Yingxia Qi, Yinong Wu, Hua Zhang and Xi Chen, Simulation of deformation of diaphragm spring grooved with spiral slits by FE method, DETC2009-86371, ASME (2009) International Conference, IDETC/CIE 2009.
12. W.J.Zhou, L.Y.Wang, Z.H.Gan, R.Z. Wang, L.M.Qui and J.M.Pfotenhauer, The performance comparison of Oxford and Triangle flexure Bearings, Advances in Cryogenic Engineering, AIP Conf. Proc. 1434, 1149-1156 (2012)