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Spring Shaft Coupling for Robotic Arm

Mechanical Torque Transmission at Variable Geometry Machines

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***Abstract* – The main aim of this research work is to provide a variable geometry coupling that transmits Mechanical Torque even at an angle of 180 degrees from the driver to the driven shaft, which changes its position or orientation, regularly or non- periodically (similar to robotic arm).**

Keywords - Full 180° torque transmission, Lubrication less angular coupling, Mechanical Torque transmission, Spring shaft coupling, Variable geometry coupling.

I. INTRODUCTION

The end effectors of modern day machines and robots need to transmit motion (mainly mechanical torque) even if the host machines or the robotic arm which changes its position and orientation continuously or in a non-periodic manner. To transmit the motion, couplings are used. For the angular torque transmission, spring shaft coupling are used and these couplings uses a rectangular section spring in order to transmit motion along the parallel shafts. The existing couplings are limited to flexibility and are complex in design. This new design paves way for implementation of shaft mechanism in variable geometry machines.

II. ADVANTAGES OVER CONVENTIONAL MODEL

A. *Conventional model*

- The conventional model uses the ‘universal joint’ in order to transmit angular motion (i.e., at different angles to achieve torque). A lot of lubrication is required for smooth motion.
- A lot of design procedures and requisites must be taken into account for their design in order to achieve great torque and operating loads.
- It is impossible to vary angles during the operation of the machines.
- The conventional model uses a lot of links and shafts to transmit motion at 180° or simply those machines which use parallel shafts.
- The mass and weight of the system is very high.
- A lot of stresses are faced in the conventional model which can lead to failure.

B. *Manufacturing difficulties in conventional systems*

- The system needs more components but only achieves motion at 30° - 45° angles.
- Special materials needed to be used to overcome the shear stresses.
- A lot of processes like casting, grinding, forging, threading and drilling are involved in the design process.
- The costs required for the machining and processing are very high.

C. *Working difficulties of conventional system*

- Rust is a major problem faced by the conventional model and it involves a lot of different components such as pins, collars, screw etc.
- It is impossible to achieve minimum differences in angular motion such as 24°, 25°, 33° etc.
- The geometry cannot be varied easily.

D. *Advantages of U-Shaft*

- Lubrication is not required as there are no risks of components getting stuck and there very little need for maintenance.
- Variations in angle can be easily achieved during the operation of the machine. This is done using springs.
- It has only one coupling shaft i.e., no additional components. A key hole can be provided for connections.
- Reduced mass and weight, since it has very less components.
- Only direct stresses act on the shaft i.e., tensile and compressive stresses since it is a single body system.
- Variation in angle ranges from 0° to 180°.
- Very simple and easy design parameters and manufacturing.

III. APPLICATIONS OF U-SHAFT

- These components are generally used in transmission of torque through rotary motion with respect to the driver shafts. They are unique in design, mass and nature of operation.
- The U-shaft can transmit motion at angles from 0° to 180° both in stable and variable geometries.
- These systems can be used in robotic arms, light weight automobile transmission systems. It can also be used in variable geometry machines.

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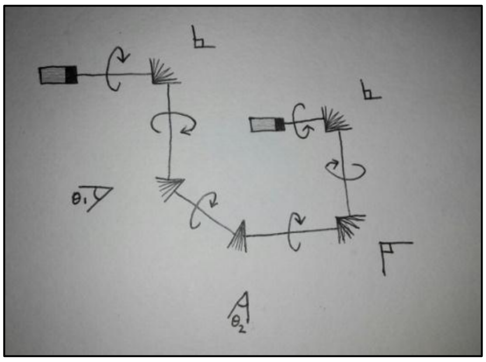

Fig 3.1 Applications of U-Shaft

A. In light weight automobile

In the light weight automobile systems, the weight/operating load is minimum and hence this type of flexible shaft can replace the propeller shaft and hence reduce the weight and maintenance requirement.

(Although the flexible shaft could not withstand the load that is variable by conventional shafts, through effective design the closest efficiency can be achieved.)

B. Completely parallel and opposite direction shafts

Using the U-Shaft the torque can be transmitted even to the parallel shafts as shown i.e., 180° motion.

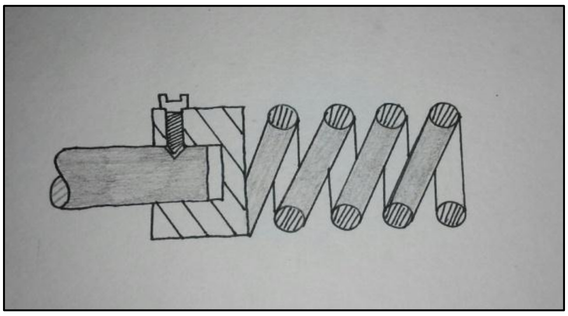

Fig 3.2 assembly of U-Shaft

C. In variable geometry machines

The variable geometry machine is an innovational concept that can form variable geometries during operations. Similar concept can be implemented to robotic arm to achieve various motions, independent of the motion transmission system connected to end effectors.

In other words the end effectors in robotic arm can be connected with this new transmission system for achieving torque transmission from the base.

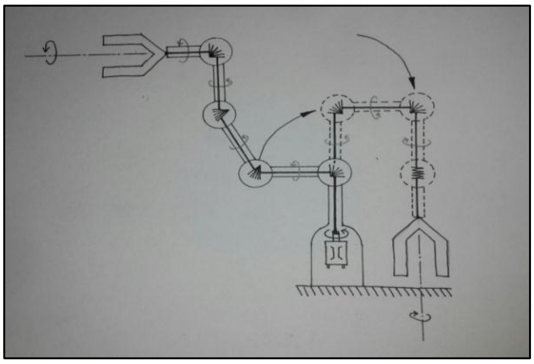

Fig 3.3 Application in robotic arm

D. In angular torque transmission for screw driving end effectors

The spring shaft coupling can be implanted as the end effectors for rapid screw driving power tool in the engine assemble sectors, for their ability to survive under variable geometry scenario

IV. RECTIFICATION OF PROBLEMS BY REPLACING EXISTING MODEL WITH U-SHAFT

A. Conventional coupling vs. new model

The conventional models use universal, knuckle joints to achieve angular torque transmissions. The new model uses springs to achieve variable angular torque transmission. The problems faced in it are:

1. Lubrication.
2. Wear.
3. Constraints.
4. Many components, complex design.
5. There are chances for disassembly of parts due to mechanical vibrations.

B. Conventional rigid gears vs. new model

In the conventional system, the gear systems are fixed i.e., it cannot produce angles dynamically during machine process. Angles are fixed an cannot be altered. Generally in this systems bevel gears, worm and worm gears are used. The problems faced in this are:

1. Fixed.
2. Meshing causes heat to dissipate.
3. Wear of gear tooth.
4. Failure of gear meshing during high torque conditions.
5. Mass and weight considerations

Hence all these conventional systems are replaced by the new torque transmission system.

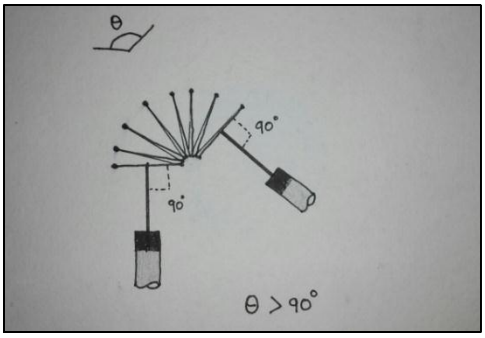

Fig 4.1 Angular operation of the coupling

V. DESIGN OF U-SHAFTS

The new model uses helical springs of rectangular/ circular cross-section to transmit the motion (mainly rotary) to adjacent or parallel shafts. The angle can be varied as per requirement and the design is very simple.

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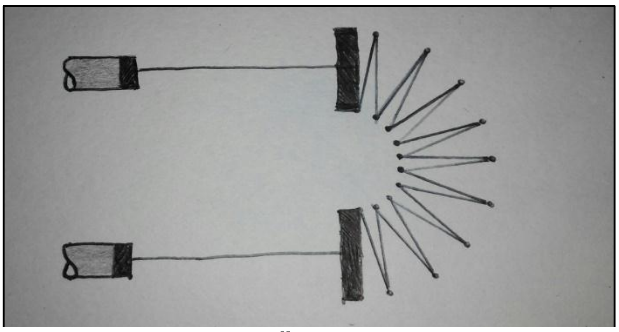

Fig 5.1 Full 180º operation

A. Parameters to be considered

1. Coil diameter vs. wire diameter or(Length x breadth x height) calculation.
2. Stiffness with respect to cross section.
3. Stresses acting over the system.
4. Torque transmission, deflection and flexibility.

B. Coil diameter w.r.t wire cross section

The general relation between the coil diameter and the wire cross-section is that, as the coil diameter increases the Moment 'M' increases because the load acts on the centre of the spring axis.

Since,

$$Moment = Force \times distance$$

$$M = F \times d$$

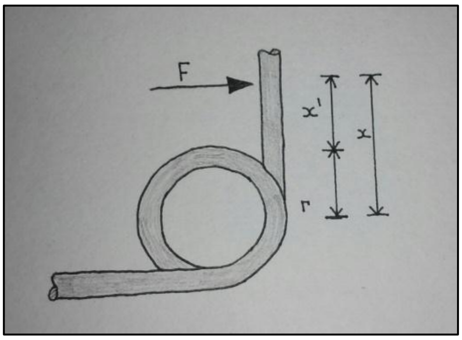

Fig 5.2 Radius w.r.t load applied

Increasing moments causes unwinding of the wire. For this reason the coil diameter or winding diameter is reduced in order to reduce undesirable unwinding of the coil during operation.

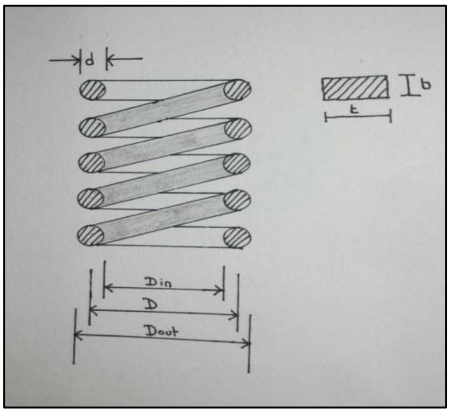

Fig 5.3 helical coil spring shaft

This phenomenon can be generally noticed in "Torsion springs". In this case, $'x'$ is the summation of x' and r i.e., diameter should be considered which is proportional to the moment.

- Small adjustments for good spring action

A small hole is to be drilled at the initiation point of the spring threading to improve the bending action at the spring surface. This is done in order to improve the working ability of spring shaft under variable positions and orientations.

- Pitch needed for 180° inclination with respect to winding diameter

1. The pitch should have 1.5 times the thickness/ diameter of the wire.
2. The U-Geometry must have a distance of $6D$ between the axes of the two parallel shafts for smooth torque transmission.
3. From the prototype it was found that the inner layer becomes less than $0.6 \times pitch$ and the outer layer becomes $1.8 \times pitch$ while working.

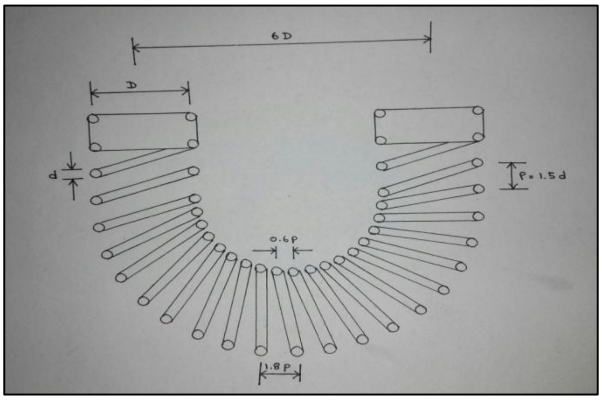

Fig 5.4 Pitch w.r.t spring thickness

- Preferred cross-sections for the coil

Both the rectangle and the circular cross-sections are unique in their properties.

For high speed operations circular cross-sections are preferred. For high moment/torque transmission rectangular sections are suitable.

In circular section the diameter of the wire is to be increased to withstand the torque against tortional force, which will proportionally increases the mass, rigidity and weight of the coupling.

Considering the requirements of the machine, the section of the wire is to be determined.

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C. Circular section vs. Rectangular section

TABLE: 1 Differences between circular and rectangular cross sections.

S.no	Parameter	Circular	Rectangular
1	stiffness	The stiffness of the spring increases as the coil diameter increases	Comparatively has a good stiffness for very less mass
2	Torque transmission	Not suitable for high torque transmission since it is susceptible to torsion which leads to unwinding of the spring	Suitable for high torque transmission. Unwinding is comparatively less.
3	Speed of operation	This type of spring is suitable for high speed operations	Not suitable for high speed transmission.
4	U-curvature of the shaft	The curvature and the distance between the shafts is comparatively less	The curvature and the distance is comparatively larger.

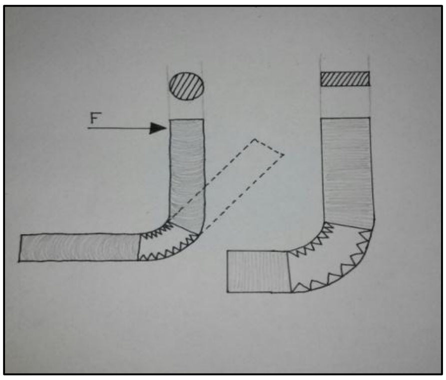

Fig 5.5 Dotted lines represent the deformation path of circular cross sectional springs.

D. Deflection

According to spring theory,

$$\delta = \frac{F}{K}$$

δ – deflection

F – force applied

In this case the spring is to be designed with respect to the stiffness and the load to be of the spring shaft (ie; force applied)

E. Stiffness of the spring shaft

The stiffness of the coupling should be maximum to survive under high torque transmission systems. Generally the spring shaft could be made of circular or rectangular sectional wire. But within the given mass and dimensions of the spring shaft the maximum stiffness can be attained only by using the rectangular sectional wire.

1. Stiffness of circular cross sectional spring shaft

$$k = \frac{G\, d^4}{8D^3 N}$$

Where,

K - stiffness of the spring
D - coil diameter
N - Number of turns
G – shear or bulk modulus
d – diameter of the wire

2. Stiffness of rectangular cross sectional spring shaft

$$k = \frac{4\, G\, t^3 b}{Q' \pi D^3 N}$$

Where,

t – thickness of the rectangular section
b – breadth of the rectangular section
Q' – factors for rectangular wire section

(note: the value of Q' varies with respect to the thickness and breadth of the rectangular wire section)

The difference between the sections with respect to their stiffness are tabulated and compared.
(Dc=90; Dr=92, t=10, b=5 and N=20)

TABLE: 2 Comparison between the sections

S.no	Material	Area (mm^2)	k (circle) (N/mm^2)	k (rectangle) (N/mm^2)
1	Aluminium	50	0.9130	2.4376
2	Titanium	50	3.8628	10.3131
3	Tungsten	50	6.2156	16.5948
4	Steel C60	50	3.1253	8.2443

From the above table it is understood that the rectangular sectional wire has good stiffness when compared to the circular sectional spring.

F. Stresses acting on the system

Tensile and compressive stresses are the only stresses that act on the spring. They are easily predictable and can be located easily. Counter measures for undesirable direct stresses can be taken wherever necessary, but in this case along with the direct stresses the spring is also subjected to tortional stress, which should be taken in to account in order to avoid the deformation of the coupling under working condition.

Here the tortional stress can be represented as σt,

$$\sigma t = \frac{6\, Kb\, M}{bt^2}$$

Where,

Kb – Whal factor
M – Bending Moment ($F \times d$)

The stability of the coupling also depends on the angular deformation rate θ,

$$\theta = \frac{\pi\, M\, D\, N}{E\, I}$$

Where,

D – mean coil diameter
E – Young's modulus
I – moment of inertia of rectangular section ($^{bt^3}/_{12}$)

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In this case the θ value should be minimum, so to achieve this condition the Young's modulus should be increased and the 'I' value should be high enough.

The 'I' value can be increased by selecting the rectangular wire of good thickness, but the Young's modulus can only be increased by choosing the right material w.r.t the work.

Hence the material selection plays a major role in the design.

VI. MATERIAL SELECTION AND DESIGN PARAMETERS

A. Material selection

Stainless steels and aluminum alloys are used as flexible coupling devices. Some of the alternative materials that can be used are given below in the table.

TABLE: 3 Properties of Materials

S.no	Material	Poisson ration (GPa)	Density kg/m^3	Young's modulus (GPa)	Shear Modulus (GPa)
1	Aluminum (Al)	0.35	2700	70	26
2	Titanium (Ti)	0.32	4507	116	44
3	Tungsten (W)	0.28	19250	411	161
4	Iron (Fe)	0.29	7874	211	82

The alloys of any two of the above material is suitable for the operation.

Example,

TABLE: 4 Properties of alloys

S.no	Stiffness	Torque	Speed	Deformation
Ti – Al	High	Moderate	High	Comparatively high
Ti – W	Less	High	High	Extremely low
Al – W	Moderate	Moderate	Moderate	Moderate

These alloys can be used to replace the existing model spring shafts which are made of conventional steel and aluminium based alloy materials.

B. Design Parameters

The helical shaft coupling can allow up to 5º to 90º of angular torque transmission with respect to the number of coils it is made of.

Generally the performance of these spring shaft coupling is determined by its; outer diameter, inner diameter, number of coils, coil thickness and material selection. With respect to these characteristics the torque capacity, angular and parallel (180º) torque transmission, torsional bending rates of shaft couplings can be modified w.r.t specific requirements.

But as the speed and the torque transmission of the machine increases, there occurs unwinding and deformation of the coupling, for these reasons the considerations of cross section and the material selection are to be done at the earlier stage and the design should be made to meet the requirements.

VII. EXISTING SPRING SHAFT COUPLING vs. NEW DESIGN

The existing spring shaft coupling can only transmit the torque up to 45º for high speed torque transmission and 90º for low speed torque transmission systems and also they have very less active windings, say 5 to 6 which make them unsuitable for transmitting torque to the shafts at an angle of 180º (ie; parallel shafts).

The new model spring shaft has been designed with respect to its compatibility with the high speed operations with heavy torque transmission. This is achieved through the selection of materials of above specified alloys and choosing the rectangular wire with 't' greater than 'b' to achieve good stiffness against the unwinding of the coupling. Also the new design spring shaft coupling is suitable for the variable geometry machines such as robotic arm to transmit the motion even when the end effector continuously changes its position.

VIII. PROBLEMS FACED & REMEDIES

A. Problems faced

1. Resonance due to natural frequency.
2. Unwinding of coil.
3. Reduction of pitch caused by compression.
4. Wear, if the spring comes in contact with the surface.
5. Smooth compression and expansion of the coupling.

B. Remedies

1. Resonance: the excitation of the spring caused by external factors cause vibrations in the system. This can be reduced by increasing the mass of the system and hence its natural frequency increases.
2. Unwinding: Due to the torsion the unwinding takes place. This can be controlled by using alloys of Al-W, Al-Ti. (Also the unwinding can be reduced to the maximum extent by replacing the circular section with rectangular section).
3. Reduction of pitch: As the system is subjected to regular compression and tension, the pitch gets varied; these sort of deflection can be reduced by increasing the stiffness.
4. Wear due to contact: when the spring comes in contact with the surfaces, wear takes place. This can be controlled by using proper elevation of the spring over the surface of the host machine.
5. Smooth compression and expansion of the coupling: From the reference, the existing model is made with drilled holes at the beginning of the threading to provide a smooth bending of the spring system. It does not influence the pitch of the spring but plays a huge role in the bending of the spring shaft.

IX. CONCLUSION AND FUTURE WORK

The presented approach solves the bending and shearing problems faced by the fixed torque transmission systems, which is a new concept in this area. Some of the future developments can be made in this transmission system are as follows,

1. Further development such as reduction in mass of the system, will reduce the space conception and makes the system handy.
2. Achieve torque transmission of rectangular section spring using the circular section spring to the maximum.
3. To make the coupling suitable for high speed machine transmission systems.
4. Further reduce the cost of machining.
5. To make it suitable for medium scale automobiles.

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