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# Closed Loop Stepper with Harmonic Gear Reducer for SME Robots

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**Abstract:** ***SME robots are special class of industrial robots suitable for SME industries meeting the needs of such industries. Recent development of Computer, Communication and Electronic industries will make the SME robot concepts a reality in future. Closed Loop Stepper motor with backlash free Harmonic Drive with triangular tooth profile is presented as suitable devices for building SME robots high endurance, speed and precision.***

**Keywords:** SME Robots, Harmonic Drives, Cyclo Drives, Closed Loop Stepper Motors, Servo Motors

## 1. Introduction

Industrial robots play a major role in large scale manufacturing industry sectors such as automobile, Computer-Communication-and-Consumer Electronic (3C), Foundry, Metal Fabrication, etc. carrying out welding, painting, product inspection, packaging, labeling, pick & place, etc. with high endurance, speed and precision. Many Small & Medium- sized enterprises are still hesitant to use industrial robots for their productivity improvements as these organizations cannot afford complex robots used by large scale industries due to a) requirement of specialized personnel to program and maintain b) limited floor space c) too expensive and payback period is too long to justify the investment. Industrial robots suitable for SME's should meet following five essential requirements [1].

i) Quick setup time
ii) Easy to program without special skills
iii) Collaborative and safe, even in small shops
iv) Flexible deployment for multiple uses
v) Fast payback for the investment

SME Robotics Initiative of European Union has initiated several research programs to manufacture Industrial Robots suitable for SME's. Although the developed countries remain as the industrial producers, more and more developing countries are becoming industrial producers, especially in labor intensive sectors like textile and clothing due to availability of cheep labor. However, cheap labor will not be available forever and hence industries in these developing countries have to adopt industrial automation solutions to maintain the competitiveness. Hence, SME robotics concept is well suited for industries in developing countries as well. Recent developments in Computer, Communication and Electronic industries offering very high speed computing power, communication capabilities at very low costs based on powerful Microcontrollers, Digital Signal Processors (DSP's), Field Programmable Logic Arrays (FPGA's), WIFI/Bluetooth devices, etc. have already created foundation layer for building the SME robots meeting above five requirements. However, very little developments related to cost reductions can be seen in other two key areas – servo motors and backlash free gear reducers – essential for building industrial robots with high endurance, speed and precision.

In this research paper, we present the feasibility of using closed loop stepper motors with Cyclo Drives and Harmonic Drives manufactured with moderate precision machining for SME robots. In Section 2, basic operation of Harmonic Drive and Cyclo Drive is discussed. In Section 3, issues related to manufacturing Harmonic Drives and Cyclo Drives are discussed and their performance is summarized. Performance of open loop steppers, closed loop stepper and servos are compared in Section 4 to justify the suitability of closed loop steppers for SME Robots.

## 2. Backlash Free Gear Reducers for Industrial Robots

An industrial robot consists of number of links connected by mechanical joints. The link assembly is mounted on a base and a wrist attached with an end-effector facilitates gripping or handling of objects. Vertically articulated industrial robots are constructed with 5 or 6 degrees of freedom using rotary joints. Gear reducers suitable for vertically articulated industrial robots are used for evaluation of backlash free gear reducers. Harmonic Drive invented in 1959 by C.W. Musser [2] is used by the industrial robot manufacturers due to its zero backlash performance. The Harmonic Drive consists of a wave generator, a flexspline and a circular spline as shown in Figure 2.1. The flexspline is a thin shallow cup with teeth positioned radially around the outside open end of the cup. The circular spline is a rigid circular ring with teeth on the inside. The wave generator is an elliptical disk with a thin outer ball bearing. The flexspline and wave generator are placed inside the circular spline, meshing the teeth of flex spline and circular spline. As the flexspline is deformed into an elliptical shape the teeth mesh only in two regions around the major axis of the ellipse. Harmonic Drive is a compact device capable of producing high reduction ratios such as 1:100. When the circular spline and flexspline have $n$ and $n-2$ teeth configuration, flexspline is rotationally fixed and circular spline is free to rotate, the device reduction ratio is $2:n$. If the circular spline is fixed and flexspline is free to rotate, the device reduction ratio is $2:(n-2)$. The device invented by Musser in 1959 consists of triangular-shaped teeth and many different teeth shapes have been patented since then. These inventions attempt to improve the load caring capability of the device. A major challenge in manufacturing the harmonic drive is machining the teeth with required accuracy. In order to maintain the flexibility of the flexspline without fatigue failures, very low gear teeth module is used.

The Cyclo Drive shown in Figure 2.2 is another compact speed reducer with high reduction ratio. In a Cyclo Drive, the input shaft drives an eccentric cam that in turn drives the cycloidal gear in an eccentric cycloidal motion. The perimeter of the cycloidal gear mesh with a stationary ring gear and the eccentric motion of the cycloidal disk is transferred to the output shaft by a set of pins placed through the face of the cycolidal gear. The two-stage cyclo speed reducer with two cycloidal disks relatively turned to each other by 180 degrees placed between a stationary ring gear and the output moving ring gear is capable of producing high gear reduction ratio without a set of rollers [3]. Further such two-stage Cyclo Drive has high gear teeth module which ease the difficulties in machining.

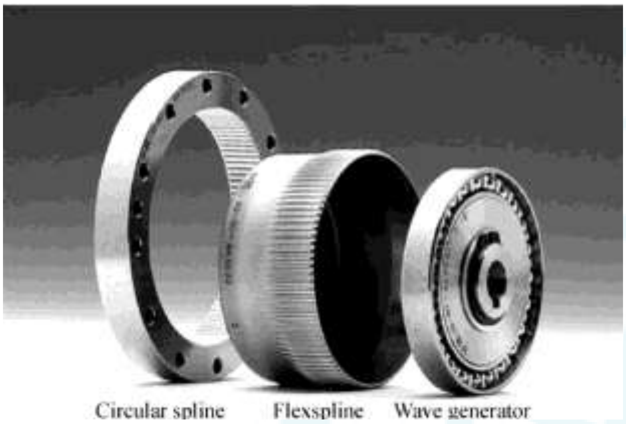
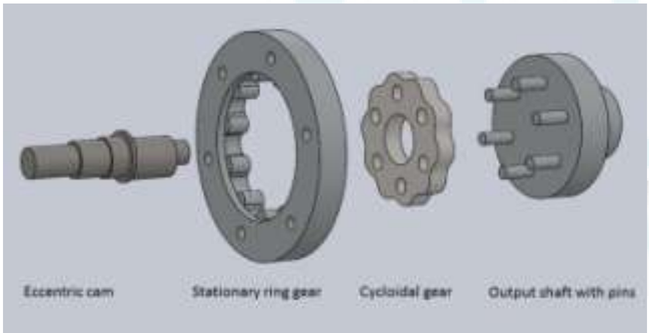
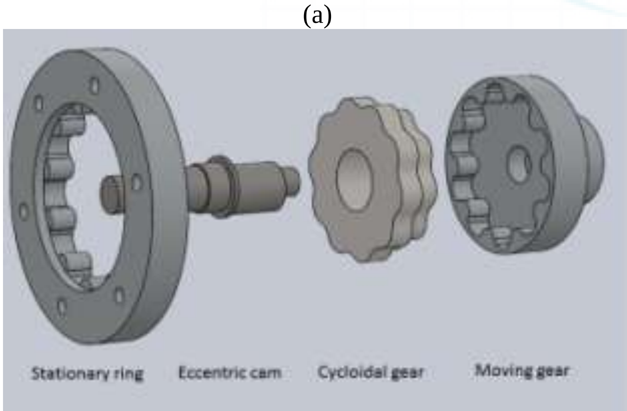



**Figure 2.1:** Major Components of a Harmonic Drive




(a)



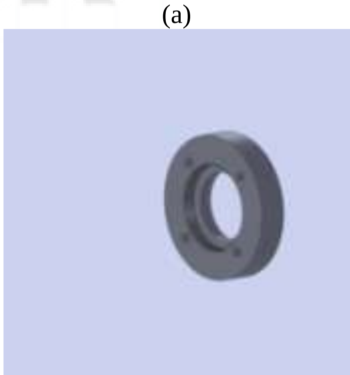

(b)

**Figure 2.2:** Major Components of a Cylo Drive (a) Single Stage (b) Two Stage

## 3. Harmonic and Cyclo Gear Reducer Manufacturing Challenges

As indicated in Section 2, the machining of the required tooth shape of low module gear teeth in Harmonic Drive with the required dimensional accuracy and surface finish is a major challenge. This challenge can be managed by selecting a suitable gear tooth profile. Having carefully studied the several tooth profiles indicated in Table 3.1, the triangular shape tooth profile proposed by Musser in his 1959 patent was selected. The major reason for selection of the triangular tooth profile was due to the possibility of removing the backlash by adjusting the elliptical disk major diameter to compensate for any machining errors. Figure 3.1 shows the designed tooth profile for a Harmonic Drive with 1:50 reduction ratio and ring diameter of approximately 35 mm. Further, as indicated in Section 2, two-stage Cyclo Drive having high gear module simplifies the machining process due to larger tooth profile radius compare to single-stage Cyclo Drive with same reduction ratio. Further, due to elimination of set of rollers in the two-stage Cyclo Drive, the manufacturing of two-stage Cyclo Drive is a simpler task than manufacturing a single-stage drive having the same reduction ratio and load carrying capacity. Figure 3.2 shows the tooth profile of a Cyclo Drive with 1:100 reduction ratio and ring diameter of approximately 35 mm. The required profiles of the cycloidal disk and ring gear can be easily machined using a CNC machining centre. Due to very low gear teeth module of flex spline and circular spline, in addition to CNC machining, wire cut and spark erosion techniques were used in manufacturing process. Figure 3.3 depicts photograph of the manufactured fine-pitched flex spline and circular spline.

(a)



(b)

**Figure 3.1:** (a) Flex Spline, (b) Circular Spline of a1:50 Harmonic Drive

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(a)

(b)

**Figure 3.2:** (a) Cycloidal Disk, (b) Ring Gear of a 1:100 Two-Stage Cycloidal Drive

(a)

(b)

**Figure 3.3:** Photographs of Manufactured Harmonic Drive Components (a) Circular Spline (b) Flexspline

**Table 3.1:** Different Tooth Profiles Considered for Study

| Source | Year |
|---|---|
| US PATENT 2,906,143 [2] | 1959 |
| US PATENT 4,823,638 [4] | 1989 |
| US PATENT 5,662,008 [5] | 1997 |
| US PATENT 8,555,505 [6] | 2013 |

In order to evaluate the manufacturability of Harmonic Drives and Cyclo Drives without backlash using CNC machining, wire cut and spark erosion, six different gear boxes from each drive technology were manufactured. We have restricted the manufacturing process to use only CNC machining, wire cut and spark erosion to manufacture gear drives at an affordable cost for SME Robots. Table 3.2 shows the ring gear diameter of these drives. Table 3.2 also depicts approximate cost, the observed backlash and evenness of the load on the input shaft under no-load condition. It is important to note that due to eccentric motion of the cycloidal disk, the load on the input shaft under no-load condition is uneven due to machining errors. On the other hand, all Harmonic Drives had even load on the input shaft under no-load condition. All Harmonic Drives showed small backlash due to spark erosion overcut. The uneven load on the input shaft of Cyclo Drive can be eliminated by introducing an overcut to the cycloidal disks, but that introduced a significant backlash. By increasing the major diameter of the elliptical wave generator, we completely eliminated the backlash of all Harmonic Drives. Therefore, we conclude that Harmonic Drive with triangular tooth profile can be manufactured using CNC machining, wire cut and spark erosion at an affordable cost for SME robots.

## 4. Closed loop Stepper Drives for SME robots

Traditionally stepper motors were used in open loop operation due to its ability to rotate step-by-step manner by exciting its windings sequentially due to its high pole count. In a stepper motor, if the available torque is not sufficient to overcome the load, motor will skip steps creating position errors. The stepper motor has high torque at low speeds (see Figure 4.1). Hence, the simplicity and low cost of stepper motors made them popular in many applications needing high holding torques and low speed operations. In contrast, servo motor is always used in closed loop operation using built-in encoders due to its low pole count. The encoders continuously communicate back to the servo controller which makes necessary adjustments to ensure target position is reached. The torque of a servo motor is constant over its rated speed range while stepper motor torque drops as the speed is increased within the rated speed range (refer Figure 4.1). Hence stepper motor operating at high speeds will skip steps and to avoid this, traditionally, stepper motors are oversized to ensure there is a large margin between worst-case load torque and the motor's available torque. Even with oversized motor, due to reduction in torque of stepper at high speeds, stepper motor will loose its stepping capability in high speed applications under unpredictable load conditions while servo motor will operate properly under unpredictable load conditions. Further, servo motor is capable of providing higher instantaneous rating where as is stepper will lose its steps beyond its rated torque. As the cost of a servomotor is high, it is used in high speed applications where significant torque is needed at high speeds.

**Table 3.2:** Summery of Twelve Manufactured Backlash Free Gear Reducers

| Gear Box Type and ID Number | Ring Inner Diameter (mm) | Load on input shaft | Backlash | Cost (Rs.) |
|---|---|---|---|---|
| Cyclo #1 | 35 | *Uneven* | *No* | 15,000/= |
| Cyclo #2 | 35 | *Uneven* | *No* | 20,000/= |
| Cyclo #3 | 45 | *Uneven* | *No* | 25,000/= |
| Cyclo #4 | 45 | *Uneven* | *No* | 30,000/= |
| Cyclo #5 | 75 | *Uneven* | *No* | 35,000/= |
| Cyclo #6 | 100 | *Uneven* | *No* | 40,000/= |
| Harmonic #1 | 35 | *Even* | *No* | 20,000/= |
| Harmonic #2 | 35 | *Even* | *No* | 25,000/= |
| Harmonic #3 | 45 | *Even* | *No* | 30,000/= |
| Harmonic #4 | 45 | *Even* | *No* | 35,000/= |
| Harmonic #5 | 75 | *Even* | *No* | 40,000/= |
| Harmonic #6 | 100 | *Even* | *No* | 45,000/= |

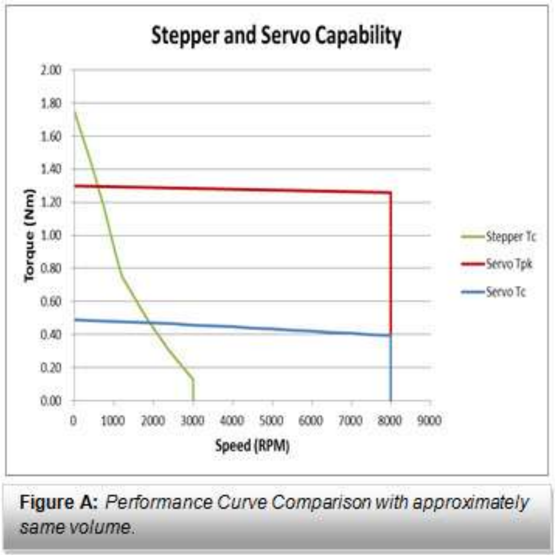


**Figure 4.1**: Performance Comparisons of Servos and Steppers with Approximately Same Volume[7]

Due to advancements in electronics where high computing power is available with low cost DSP chips and FPGA chips, researchers are now looking into operate the stepper motors under closed loop conditions by adding an encoder. Closed loop stepper motors eliminate many of the disadvantages of traditional open loop stepper systems, making them similar in performance to servo motors. Few motor manufacturers are marketing such products and StepSERVO and Leadshine are two such brands. According to published data sheets [8] for stepper motor with encoder feedback, motor torque is increased by a factor of 1.5 approximately at low speeds and by a factor of 2 at high speeds, sees Figure 4.2.

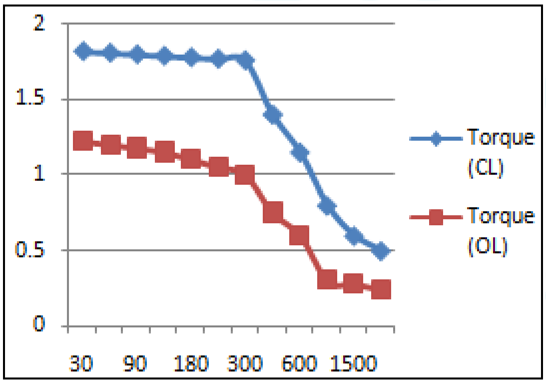


**Figure 4.2:** Torque vs. RPM Curve for Leadshine 57HS13 Motor with EM Series Stepper Driver

Based on these facts, we have estimated the closed loop stepper torque and Figure 4.3 compares it with a similar sized servo. From this figure, it is clearly visible that closed loop stepper will outperform the servo below 2000 rpm and servo motors outperform closed loop stepper above 3000 rpm. In applications where cycle time is high and accelerations are moderate, closed loop stepper is a good candidate for SME robots. For example, a closed loop stepper operating at 1500 RPM and with a 1:50 harmonic drive, output shaft will operate at 30 RPM or 0.5 RPS. This means a joint can make a 180 degree turn within 1 sec.

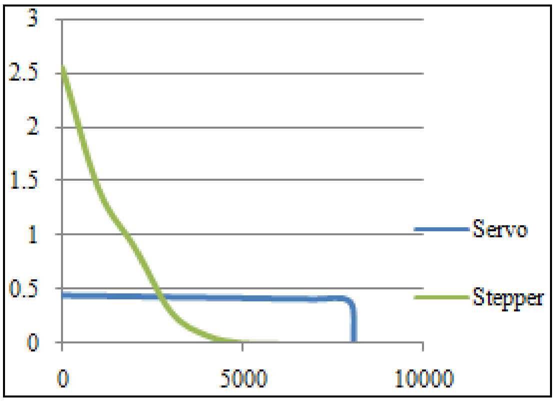


**Figure 4.3:** Torque vs. RPM for Closed Loop Stepper Compared with a Similar Sized Servo

## 5. Conclusions

Backlash free Harmonic Drives with a triangular tooth profile suitable for SME robots were manufactured using CNC machining, wire cut and spark erosion methods. Feasibility study carried out using published data for closed loop stepper motors shows that Harmonic Drive and Closed Loop Stepper combination is suitable for building SME robots when the maximum motor speed requirement is below 2000 RPM.

## References

[1] 5 Robotic Essentials for SME Manufacturers, https://blog.universal-robots.com/5-robotic-essentials-for-sme-manufacturers, browsed on 10th Nov 2017.
[2] C.W. Musser, et.al, Strain Wave Gearing, US Patent No. 2,906,143, 1959.
[3] Micro Blagojevic, et.al, A New Design of a Two-Stage Cycloidal Speed Reducer, Journal of Mechanical Design, Vol. 133, Aug. 2011.
[4] Shoichi Ishikawa, Tooth Profile of Spline of Strain Wave Gearing, US Patent 4,823,638, 1989.
[5] Joseph J. Aubin, et.al. Extended Contact Harmonic Drive Device, US Patent 5,662,008, 1997.
[6] Shoichi Ishikawa, Maximum Meshable Tooth Profile Having Non-Positive Deflexing in Flat Wave Gear Device, US Patent 8,555,505, 2013.
[7] Hurley Gill, Stepper Motor or Servo Motor: Which should it be?, White Paper, Kollmorgen-2016.
[8] Stepper Product Catalogue 2015/2016, Lead Shine Technology Co., Ltd.