Historical & Technical Analysis of Harmonic Drive Gear Design

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Abstract. This paper presents a historical and technical analysis of the Harmonic Drive Gear Design by taking into consideration the original patent by Clarence Walton Musser, the inventor of "Strain Wave Gear" and by studying a performance evaluation of it. The main original design peculiarities are highlighted, and the main characteristics are outlined using a numerical analysis of the operation principle and its efficiency.

Keywords: History of Gears, Mechanical Transmissions, Harmonic Drive Gear, Modelling, FEA Analysis, Student Paper

1 Introduction

The gear technology addresses interest also in terms of historical investigations to give merits to achievements and to track evolutions towards new solutions, as reported in a wide literature with papers, books and encyclopedia chapters. A specific interest is addressed to Harmonic Drive gear design as an emblematic example of modern achievements that have been requested and stimulated improvements and new solutions in mechatronic machines.

In this paper the peculiar history of Harmonic Drive design is presented referring to its inventor Clarence Walton Musser and his original patent designs. In addition, a technical analysis is worked out to explain the original principles of structure and operation of a Hormonic Drive by also giving an example of an evaluation of today efficient solutions.

2 Original Concept by Musser

In January 1955 Clarence Walton Musser announced the new design and then in 1957 received a patent for a mechanism called "Strain Wave Gearing" which was later referred to as "Harmonic Drives", since a use of flexible geared wheel with harmonic response. Official information about the patent was issued in 1959 as it is illustrated in Fig.1, [1]. At that time even the combination of the words "Strain Wave Gears" was a puzzle and raised a lot of questioning since mechanical engineers were used only to the law of "rigid-body mechanics" for traditional gears systems. This meant that flexibility was considered driven out from the gearing system and design.

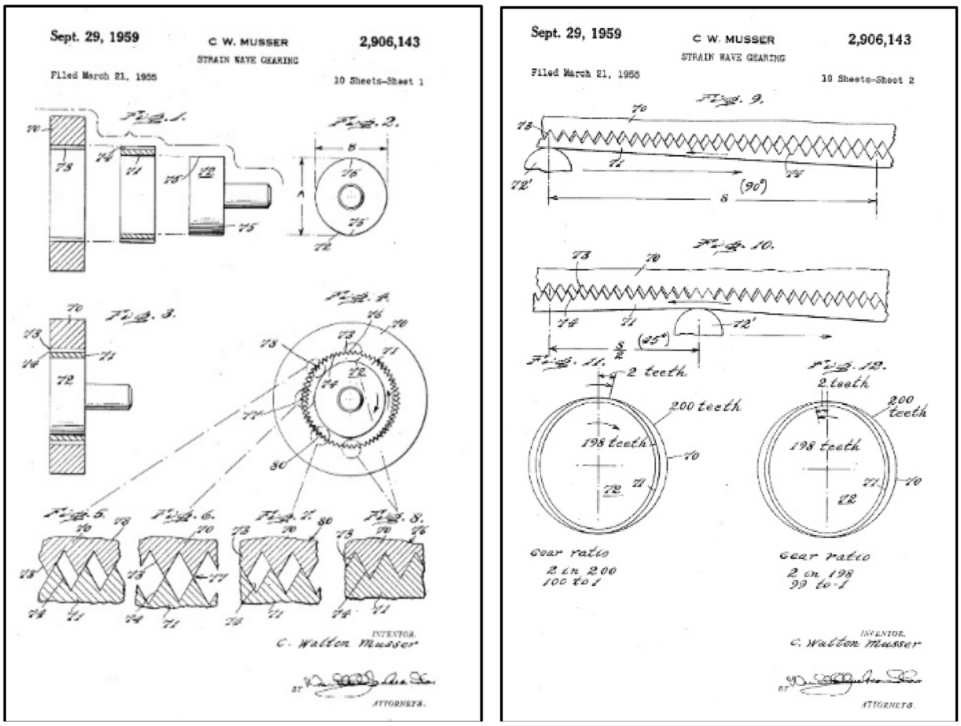
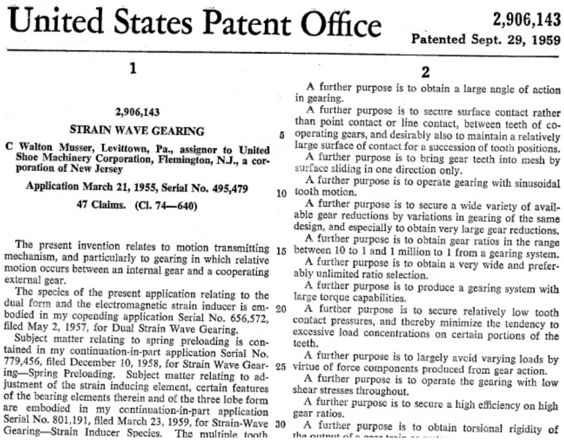


Fig.1. Main drawings in the patent of 1959 by Clarence Walton Musser [1].

In 1960, almost 5 years after the basic patent was released, Walton Musser published a paper "Breakthrough in Mechanical Design: The Harmonic Drive" [2] where for the first time, he explained the operation principles and mechanism as "A continuous deflection wave generated in a flexible spline element achieves high mechanical leverage between concentric parts".



United States Patent Office

2,906,143
Patented Sept. 29, 1959

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2,906,143

STRAIN WAVE GEARING

C Walton Musser, Levittown, Pa., assignor to United Shoe Machinery Corporation, Flemington, N.J., a corporation of New Jersey

Application March 21, 1955, Serial No. 495,479

47 Claims. (Cl. 74—640)

The present invention relates to motion transmitting mechanism, and particularly to gearing in which relative motion occurs between an internal gear and a cooperating external gear.

The species of the present application relating to the dual form and the electromagnetic strain inducer is embodied in my copending application Serial No. 656,572, filed May 2, 1957, for Dual Strain Wave Gearing.

Subject matter relating to spring preloading is contained in my continuation-in-part application Serial No. 779,456, filed December 10, 1958, for Strain Wave Gearing—Spring Preloading. Subject matter relating to adjustment of the strain inducing element, certain features of the bearing elements therein and of the three lobe form are embodied in my continuation-in-part application Serial No. 801,191, filed March 23, 1959, for Strain-Wave Gearing—Strain Inducer Species. The multiple tooth

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A further purpose is to obtain a large angle of action in gearing.

A further purpose is to secure surface contact rather than point contact or line contact, between teeth of cooperating gears, and desirably also to maintain a relatively large surface of contact for a succession of tooth positions.

A further purpose is to bring gear teeth into mesh by surface sliding in one direction only.

A further purpose is to operate gearing with sinusoidal tooth motion.

A further purpose is to secure a wide variety of available gear reductions by variations in gearing of the same design, and especially to obtain very large gear reductions.

A further purpose is to obtain gear ratios in the range between 10 to 1 and 1 million to 1 from a gearing system.

A further purpose is to obtain a very wide and preferably unlimited ratio selection.

A further purpose is to produce a gearing system with large torque capabilities.

A further purpose is to secure relatively low tooth contact pressures, and thereby minimize the tendency to excessive load concentrations on certain portions of the teeth.

A further purpose is to largely avoid varying loads by virtue of force components produced from gear action.

A further purpose is to operate the gearing with low shear stresses throughout.

A further purpose is to secure a high efficiency on high gear ratios.

A further purpose is to obtain torsional rigidity of

.a) b)

Fig 2. (a) A portrait of Clarence Walton Musser; (b) The title page of 1959 patent, [1].

Clarence Walton Musser was born on 1909 in Lancaster, Pennsylvania (USA). He grew up on a farm where he spent many hours in his father's workshop which led him to studying topics of his specific interest. At the age of 10, Walton Musser sketched and crafted his first invention that was on a rubber band gun. He studied in several universities including Chicago Technical College, MIT, and University of Pennsylvania. In the early 1930's he worked in a tool and die shop under a cruel foreman who gave him the worst jobs during a period he later recalled as "some of the best training" of his career. This experience taught Musser to work under pressure and to solve difficult problems on his own as a self-education that paid off when he began work on his many other inventions [5].

In 1935 he started his own company designing and manufacturing special machinery as a prolific inventor. The greatest of those inventions, which came in 1957 can be considered leverages with elastic deflection. In 1955 Walton Musser invented the strain wage gear and received a patent as shown in Fig.2(b). As a research adviser at United Shoe Machinery Corp., he explored non-rigid-body mechanics, using controlled deflection as an operating medium for manufacturing.

3 Structure and Operation

A Harmonic Drive (HD) is made of three main components shown in Fig.3. These components include: a Circular Spline, which is a rigid crowned ring; a Flexspline, which is a flexible thin-walled cylinder whose teeth mesh with the circular spline teeth; and the Wave Generator which is a thin raced ball bearing fitted on the elliptical plug generating a high input torque to the whole system.

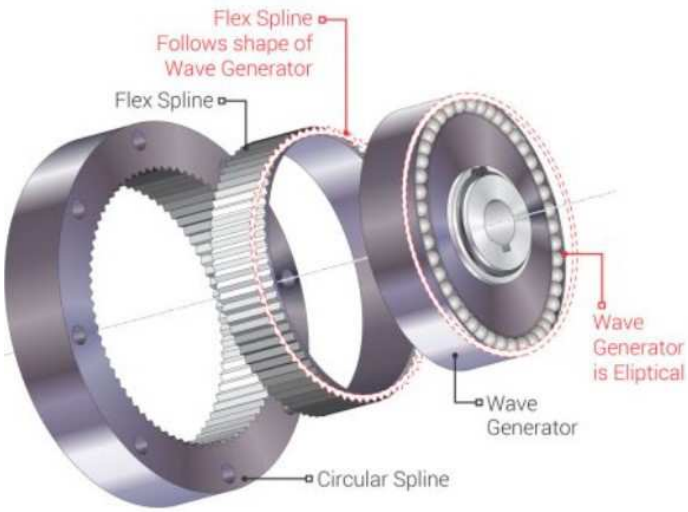


Fig 3. The basic structure of a Harmonic drive, [7]

The Harmonic Drive is basically dependent on the elastic behavior that is due to the flexibility of metal. This property is a result of significant flexibility of the flexspline walls at the open end and its teeth positioning radially around its outside. The flexspline fits tightly over the wave generator so that it deforms with the shape of the rotating ellipse but does not rotate with the wave generator. On the other side the circular spline is a rigid circular ring that is expected to be stationary regardless of the flexspline movements. The flexspline and wave generator are placed inside the circular spline, meshing the teeth of the flexspline and those of the circular spline [3]. The joint connecting flexspline and wave generator can be considered as a pseudo-revolute kinematic pair. In fact, the kinematic element of the flexspline is flexible and adapts to the quasi-elliptic shape of the wave generator. A kinematic structure of the single stage harmonic drive gearing can be represented by means of the graph shown in Fig 4(a), bearing similarities with the one of a basic epicyclic gear (EG) drive in Fig 4(b).

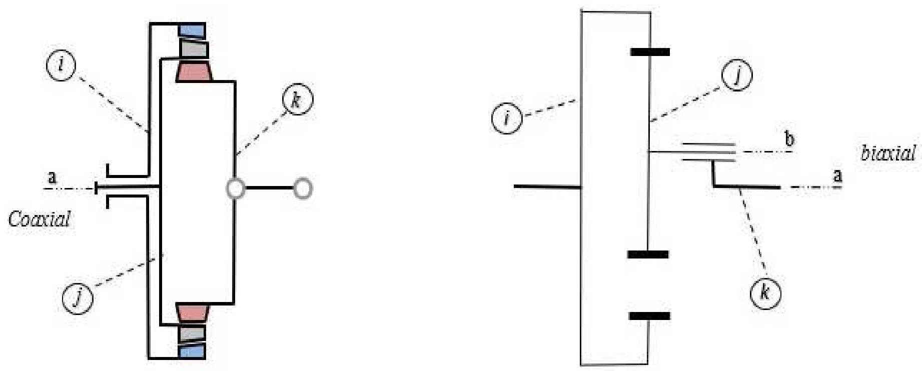


Fig 4. Kinematic design of: a) single stage harmonic drive; (b) a conventional epicyclic gear drive kinematic structure.

The meshing gears are those cut on the spline and flexspline whereas the wave generator plays a role almost like a gear carrier (coaxial). However, within the basic EG the axes of the revolute joints are on different levels (i.e., not coaxial). With the simplification discussed above, all the HD revolute joints axes are placed on the same level [6]. It is assumed that the class of combined harmonic-epicyclic gear trains herein considered obey the Grubler's degrees-of-freedom as

$$m = 3(l - 1) - 2J_R - J_G \quad (1)$$

where m represents the degree-of-freedom; l, the number of links; J_R and J_G are the number of revolute and gear pairs, respectively. A simple analysis reveals that, in its simplest form, the HD device has l = 3 links, two coaxial revolute joints (J_R= 2) and one gear pair (J_G= 1). Therefore, referring to Fig 4a, the basic model of HD, once the support frame is considered, features a single degree-of-freedom as per m = 1.

The dimensions and weight of the Harmonic Drive parts are smaller than those of other transmission devices with similar kinematic and power characteristics. For this reason, the distinctiveness of the Harmonic Drive spans a wide range of application in early and modern devices. Regardly, there has been several developments in the field of industrial engineering that offer improved options in terms of performance and efficiency. The zero-backlash property is a feature that makes it popular in robotic system yet. Among these, there is a new class of joint torque sensors embedded in Harmonic Drive using order tracking method as for example in robot arm of Fig 5, [8].

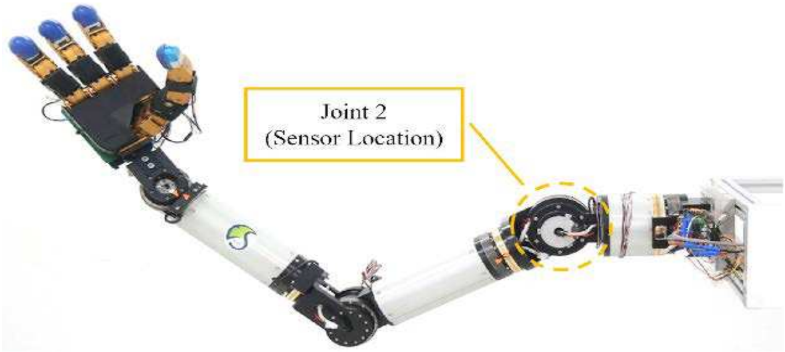
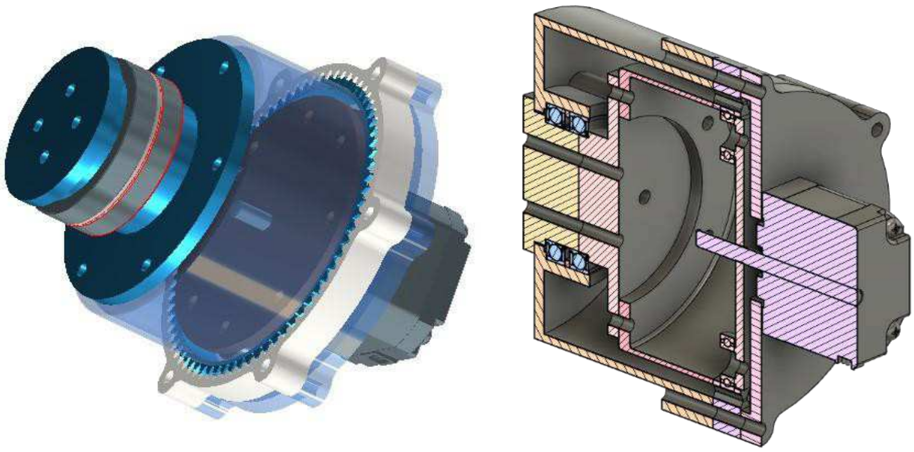


Fig 5. An example of integrated Harmonic Drive and torque sensor in robot joint, [8].

4 Harmonic Drive Model

A model of the harmonic drive has been elaborated with Autodesk Fusion360-engineering software 2021 [4]. After modelling, all the parts are assembled in Autodesk Inventor as shown in Fig 6. Generally, all the parts are made of steel as material except for the flexspline which is made of a flexible stainless steel. Color appearances in Fig. 6 were added to easily differentiate the components and the parts from each other.



. a) b)

Fig 6. The modelled Harmonic gear drive assembly: (a) mechanical design; (b) a cross-section view

5 Finite Element Analysis

The here-in presented 3D simulation focuses on the displacements, reaction forces and stress analysis for a case with a given input torque of 100 Nm. Data are reported in terms of maximum and minimum values of these parameters expected to be below the yield strengths of the assumed materials for a safe operation. In particular, the circular spline and wave generator are assumed made of steel with yield strength of 207 MPa and shear modulus of 80.76 GPa, and the Flexpline is assumed made of stainless steel with yield strength of 250 MPa and shear modulus of 74.23 GPa. A simulation was carried out for a typical operation using Autodesk Nastran-2021 engineering simulation software. The circular spline was locked using constraints and the flexible spline was loaded with a torque of 100 Nm, first in the direction of rolling of the gear, then in the opposite direction for the wave generator. The Fig.7 shows the computed displacements and deformations after the simulation has been completed with numerical results and Fig.8 illustrates the variation of the displacements recorded on the wave generator's bearings.

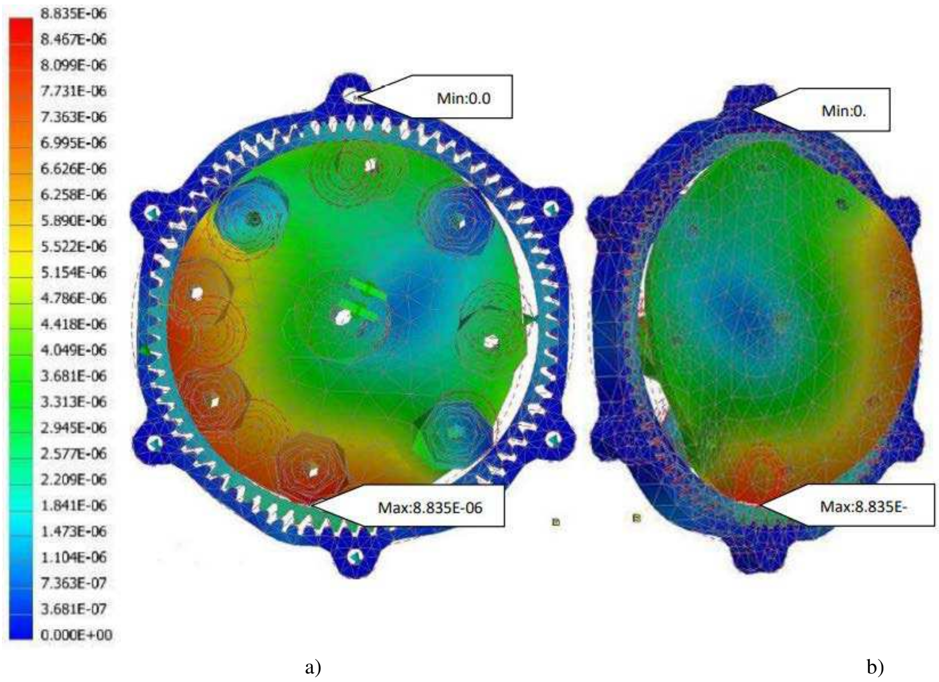


Fig 7. Computed displacement and deformation in a simulated typical operation: (a) Front view; (b) Rear view

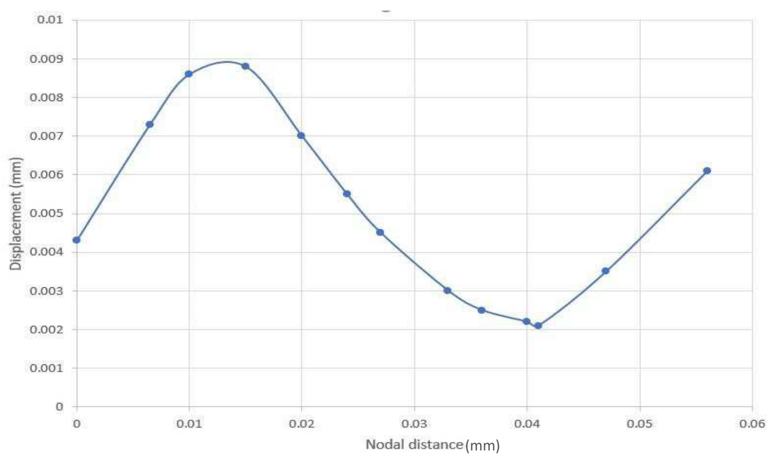


Fig 8. Graph showing recorded displacements of bearing vs nodal distance

Figs 9 and fig 10 show results on the applied load and contact forces analysis, respectively. Firstly, the contact forces are considered between the teeth of the flexspline and the circular spline. However, the interference between the gear teeth is very large due to the software's limitations. Thus, the reaction force values that were extracted from one flexspline tooth (it is expected similar action to the all the teeth) are not accurate and the relative stress error was of 0.1974 MPa, which is indeed a small value.

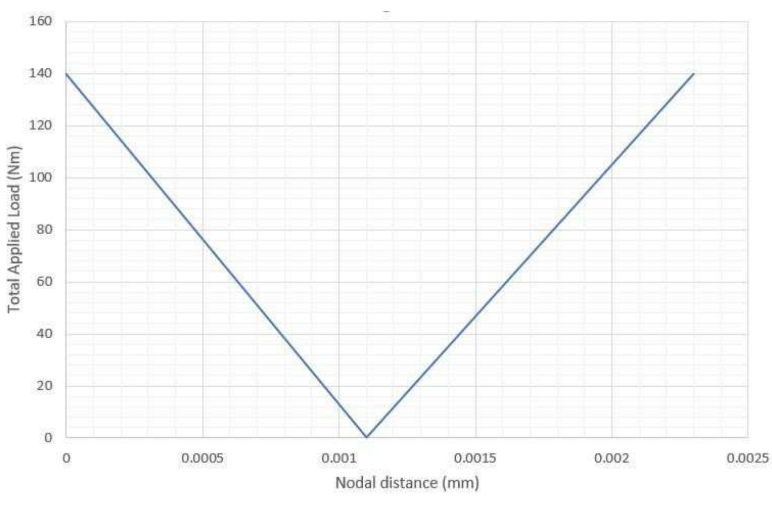


Fig 9. Trend of computed applied loads on the flexspline's tooth

In the stress analysis, the maximum stress value by Von Mises, was computed as 167.5 MPa in the region of the bearings and outer flexible bearing ring. This is a well satisfactory result considering the ultimate tensile strength of about 345 MPa for the assumed steel in the simulated mechanical design.

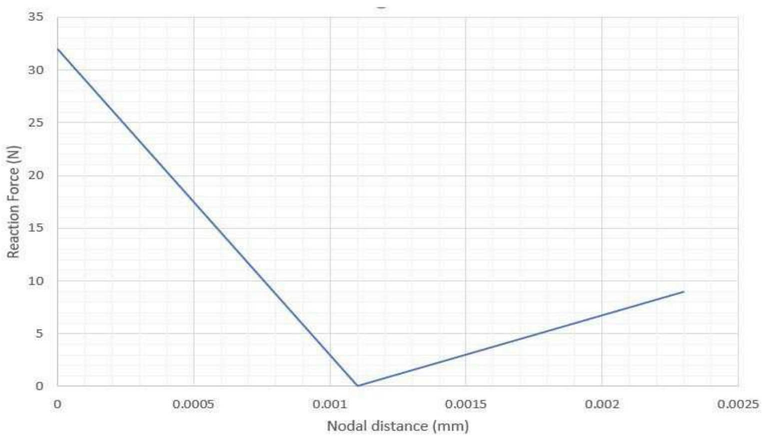


Fig 10. Computed reaction forces on the flexspline's tooth

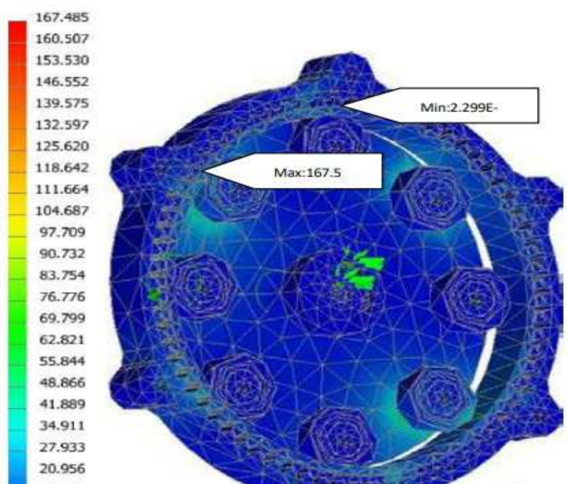


Fig 11. Computed Von Mises stress across the harmonic drive's main components for a simulated typical operation

6 Conclusion

This paper summarizes a historical-technical evaluation of Harmonic Drive gearing design by outlining the sources of the conception by its inventor Clarence W. Musser and the main operation characteristics. It took quite a while to have the Harmonic Drive transmission to be well understood and then it has been and it is yet widely used in many mechatronic systems. A typical operation has been simulated to characterize the performance in terms of teeth stress well below the strength limits, motion high transmission ratios, and reaction forces within the mechanical design.

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