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ECONOMICAL HIGH ROBUSTNESS AND PRECISION LINEAR GUIDE

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Rezumat. *Mediul de afaceri modern cere sisteme de producție care propun o utilizare facilă, sunt flexibile, au productivitate ridicată, fără mentenanță sau una redusă și care pot fi amortizate în timp scurt. Lucrarea de față descrie o soluție pentru un sistem mecanic automat, care poate genera o mișcare rectilinie de precizie, de o manieră economică, fără mentenanță, capabil să funcționeze în mediu puternic contaminat cu particule fine de praf și pulberi.*

Abstract. *Today's business environment demands production systems that are easy to use, flexible, yield great output, require little to no maintenance and provide great return of investments in short periods of time. This work focuses on providing a solution for a linear guide that is economical, light weight, precise and maintenance free. The guide comes within the scope of developing an automated linear axis that may be used in a heavily air borne contaminated environment.*

Keywords: Linear guide, flexure, maintenance free, high accuracy.

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1. Introduction

Production machines have historically been built out of long-lasting materials with many decades of use in mind. These machines are expensive, making them a risky investment, cover their costs over long periods of time, provide great risks of rapidly becoming technologically obsolete and generally require large factory floor footprints. Industry 4.0 brings new meanings to fabrication technologies, focusing on flexibility and performance rather than longevity and absolute quality. The new paradigm promises fast responses to change, enabling the industry to better follow an ever-increasing market dynamic. New machines are based on ultra cost efficient materials, such as polymers and construction steels and take advantage of highly complex electromechanical subassemblies that compensate for lack of either mass or rigidity or even both. Additive manufacturing can provide significant benefits by allowing the generation of lighter, stiffer and more robust mechanical bodies. The outcome are lighter, smaller, lower cost machines that eliminate the risks normally associated with classical production machines.

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Within this new approach, the present work brings up a new possible design, that aims at lowering the costs and weight of a linear guide, allowing machines to be build on Industry 4.0 grounds.

Everybody thinks that the new industrial revolution is purely informatic: "Take your business to the cloud and you're there!". In my research I have spoken with dozens of business people that were all convinced that new information technologies alone are the construction elements of the new revolution. Words like cloud, augmented reality, real-life simulation, artificial intelligence, edge computing make the bread and butter of revolution preachers. Yet, no previous industrial revolution has ever been conducted without a new kind of mechanical system. The first revolution was purely mechanical and achieved the mechanization of agriculture industry. The second revolution was truly a spectacular one, transforming the world like nothing before. At the core of it lied the internal combustion engine. No hand will ever go tired again!

The third industrial revolution pushed our living standards and science to new unimaginable heights. The change would come from the tiniest of things: the microprocessor and its embodiment in the form of computers. It gave rise to the smart factories we know today, with the introduction of automated equipment and robotics. So, the fourth industrial revolution, what is it going to be? Or is it happening right now? Arguably, the new revolution is powered by Internet, and it already changed our life’s completely, allowing us to connect in ways never imagined before. The world has shrunk under our very eyes.

All of a sudden, everything is reachable and tangible. But when it comes to industry itself, no revolution was ever complete without the introduction of a new type of physical system (let's call it a "machine"). No cloud, augmented reality, simulation, and the like will have a strategic impact without a solid base in the real world. I believe that the new era promised by the Industry 4.0 will be impossible without a significant change in the way we see and use manufacturing equipment itself. I believe that a new breed of machines is needed to harvest the potential provided by new information technologies, one that would allow the construction of a new and different manufacturing paradigm. These new machines need to be as flexible, as movable, as transparent, as coherent and as powerful as the information technology itself.

2. Requirements

The linear guide will be used inside an automated woodworking machine and has the following requirements:

- >= 350mm stroke;
- Strict cost constrains;
- Ability to work in heavily saw dust polluted environments;
- No maintenance over a period of 5 years;
- Lightweight construction;
- +/- 25μm linearity error over 350mm;
- Medium stiffness (above 1N/μm).

3. Proposed draft solution

The solution proposed is based upon the interaction of two elbow structures, each providing a motion with two degrees of freedom. Placing them at an angle, provides for a single line of motion as depicted in Fig. ***1***.

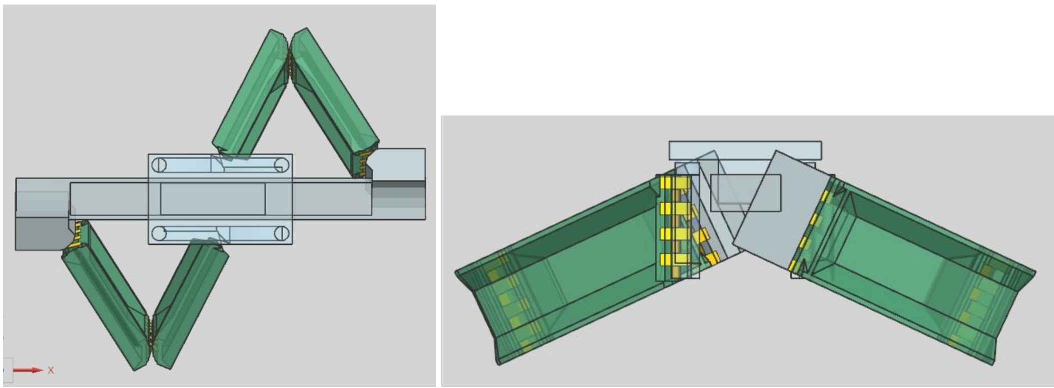

Fig. 1 Double elbow flexure based structure.

The joints are build based on cross-axis flexural pivots which provide for long life, no backlash, immunity to saw dust particles and along with elbow beams, build a cost-effective linear motion solution [1]. Compliant mechanism bring many advantages to a mechanical system such as [2]: ease of manufacturing, reduction in part count, diminished friction and low wear. The elbow beams can be constructed out of cast epoxy granite or out of construction steel beams. There are 3 cross-axis flexural pivots per elbow, each formed by four pairs of 51mm length (l), 20mm width (u) and 0.4mm thick (t) spring steel flexible strips that cross each other at their midpoints effectively forming a virtual "pin joint". If we consider the base width to be w and r to be the distance between two beams, according to [3], virtual pin joints can be used successfully to model the system in a simple and direct way (Eq. 1):

$$l = w\sqrt{1+\left(\frac{r}{w}\right)^2} \tag{1}$$

Bending resistance of the pivot may be modeled as a torsional spring, provided by Equation 2:

$$K = \frac{kEI}{2l}, \tag{2}$$

Where, E is Young' modulus, l is the length of the flexible steel strips, I represents the moment of inertia of the flexible steel strips and k is a stiffness coefficient and is, according to [3], provided by the equation:

$$k = 5.300185 - 1.6866\frac{r}{w} + 0.88536\left(\frac{r}{w}\right)^2 - 0.2094\left(\frac{r}{w}\right)^3 + 0.018385\left(\frac{r}{w}\right)^4$$

The life expectancy of the pivot is directly proportional to the stress developed in the flexible steel strips [4], and according to [3], its maximum value may be expressed as:

$$\sigma = \frac{S\theta Et}{2r} \tag{3}$$

Where θ is the maximum angle and S is the stress coefficient expressed as:

$$S = 0.062998 + 1.884218\frac{r}{w} - 1.43653\left(\frac{r}{w}\right)^2 + 0.551786\left(\frac{r}{w}\right)^3 - 0.10523\left(\frac{r}{w}\right)^4 + 0.007889\left(\frac{r}{w}\right)^5 \tag{4}$$

Using the Finite Element Method, we can gain an insight about the way the cross-axis flexural pivots behave in relationship to their dimension parameters, especially w and l while r is kept constant.

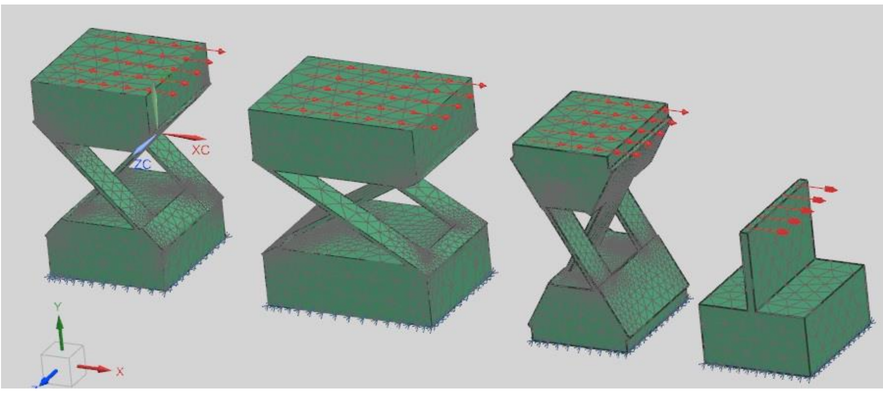

Fig. 2 Mesh of cross-axis flexural pivots with different w and l

Fig. ***2*** shows the mesh and the loads applied to a few test specimens that have varying base width and flexible steel strips length. The first specimen has a right angle between the flexible strips, the second has 120deg between the flexible strips, the third has 60deg between the flexible strips while the last is only a simple single strip flexural pivot for refence. All the specimens have the same load applied. We are interested in the differences between the responses of the four specimens and not the absolute value provided by each.

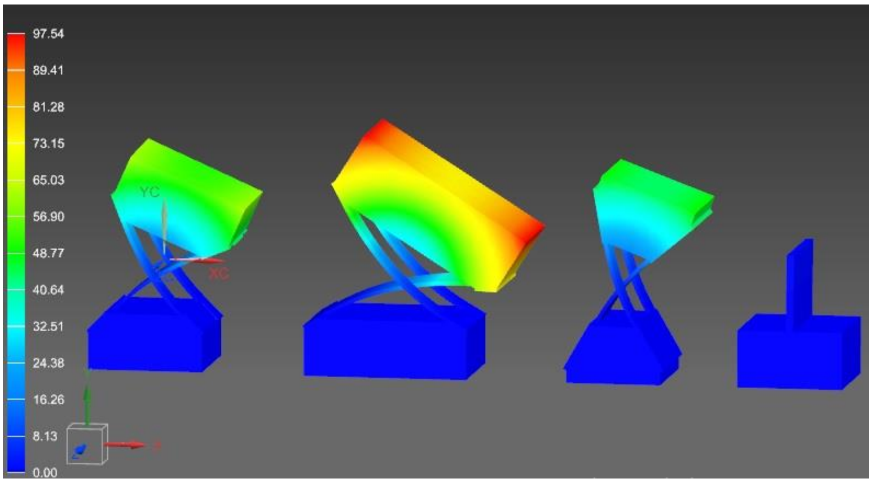

Fig. 3 FEM analysis of the four specimens - maximum deflection.

Fig. ***3*** shows the maximum deflection of the test specimens under the same applied load. We can easily conclude that the bigger the angle between the flexible strips is, the bigger the deflection will be.

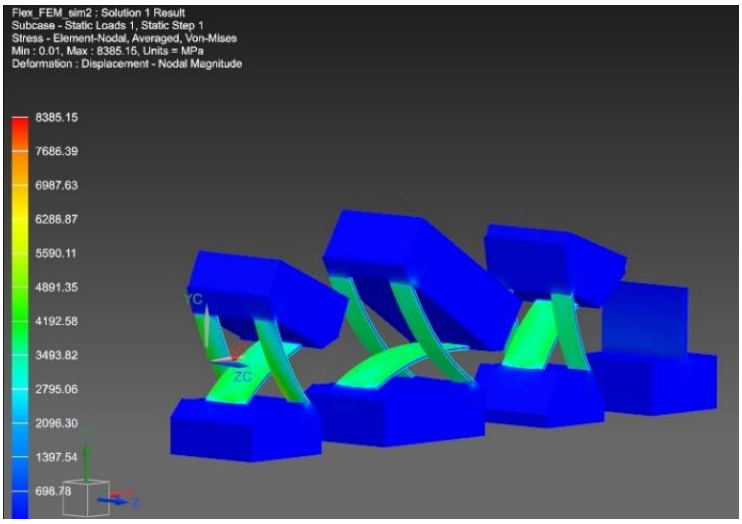

Fig. 4 FEM Analysis of the four specimens – stress under horizontal load.

Fig. ***4*** shows that the stress is nearly identical in the flexible strips while bending under the same horizontal load. In this case, the life expectancy of the cross-axis flexural pivots should be the same. Since the 120deg specimen provides the biggest deflection, it seems to be the best option.

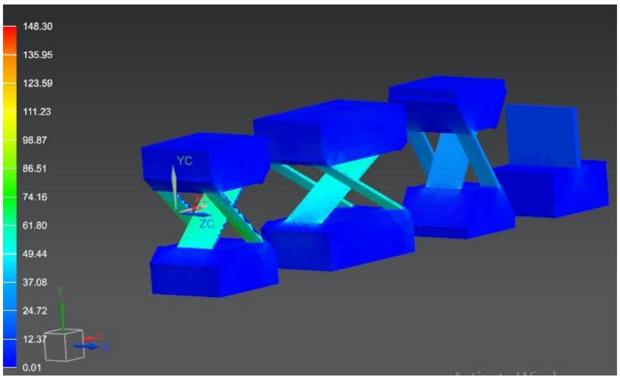

Fig. 5 FEM Analysis of the four specimens, stress under vertical load.

However, as Fig. ***5*** indicates, the stress under vertical load shows that the bigger the angle between the flexible strips is, the larger the stress under vertical load would be. Since we need both good flexural performance along with good rigidity of the joint, a possible solution would be to use the 120deg setup and increase the number of cross-axis flexural pivots pairs, until satisfactory stiffness is achieved.

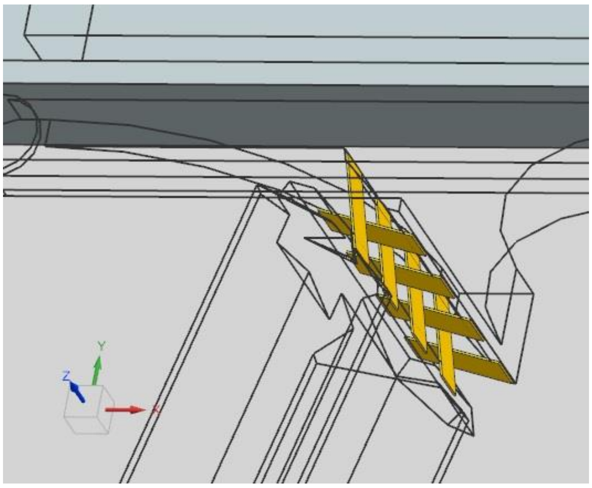

Fig. 6 Pivot joint with four cross-axis flexural pivots pairs.

A good result is found when using four cross-axis flexural pivots inside the pivot joint, as depicted in Fig. ***6***.

4. Damping

A good linear axis should have besides good rigidity and accuracy, also a good vibration damping characteristic. The double elbow design has many advantages as indicated in the previous chapters, but it lacks in terms of vibration damping. The “suspended” nature of the guide makes it act like a guitar string, fixed at the ends and free in the middle. To correct this behavior, the guide makes use of a special channel positioned along the movement axis. The channel is stationary and may be fixed along its entire path. Moving inside the channel is a block attached to the axis. Between the block and the channel is a small gap that traps a fluid. The block vibrates with the moving guide and transfers the energy of the vibrations to the fluid using the Squeeze Film Damping mechanics in vertical and horizontal directions. To improve on the damping characteristic, magnetorheological fluid may be used along with an electronically operated magnetic field generator in the block, which changes the fluid viscosity in response to the frequency spectrum of the vibration, see Fig. *7* [5].

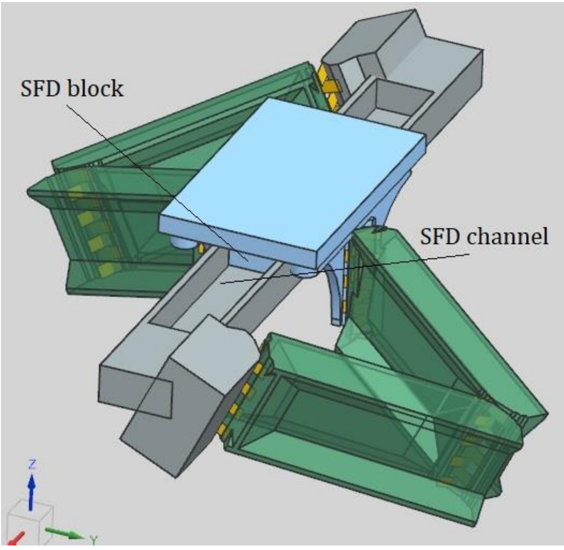

Fig. 7 Squeeze Film Damping – vibration damping channel and block.

5. Conclusion

This work presents a new and original approach towards a possible solution for a low weight, accurate, low cost, maintenance free, rigid, long life and vibration damped linear guide. Linear motion powered by compliant mechanisms are widely regarded as only feasible for short strokes, of only a few millimeters. The mechanism at hand tries to improve existing designs by providing a stoke in the hundreds of millimeters range. This approach thorough, only provides two points of support, making the full system prone to vibration. This downside is mitigated with an innovatory SFD based vibration damping system. The design is in its draft phase and many possible problems are not apparent yet. However, at this point the design seems to provide a promising alternative to the classical solutions with many added benefits.

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