Carbon Nanotubes as Machine Elements – A Critical Assessment

P.V.M. Rao, Manvinder Singh, Vijay Jain

Department of Mechanical Engineering,
Indian Institute of Technology, Delhi
New Delhi -110 016, India
pvmrao@mech.iitd.ernet.in

ABSTRACT

Gears, Bearings, Springs, Fasteners etc. are some of the typical machine elements used to build machines and mechanical systems. The function of these machine elements is to transmit motion, to support moving members, to store energy, to join two components etc. Carbon nanotubes can be used as these machine elements when building nano-machines or nano-mechanical systems. In this paper we review and do a critical assessment of past work done on use of carbon nanotube as machine elements. The suitability, advantages and limitation of carbon nanotube for each category of machine elements is discussed. The paper also discusses future directions of research in building nano-machines and nano-mechanical systems using carbon nanotube based machine elements.

Keywords: nanotubes, nano-mechanical systems, nano-machines, carbon nanotube.

1 INTRODUCTION

Machines built at the molecular level have been contemplated extensively in the past few years [1]. Carbon nanotubes can be used as building blocks for realizing machines and mechanical systems at a nano level. Ever since the preparation of carbon nanotubes (CNTs), also known as buckytubes, first reported by Iijima [2], they have attracted unprecedented attention for there unique attributes namely mechanical, electrical and physical attributes [3,4]. CNTs are needle like tubes and can be thought of as sheets of graphite rolled into cylinders and capped at both ends. CNTs can be single wall (SWNTs), double walled (DWNTs) or multiple walled (MWNTs). A wide variety of applications have been suggested for CNTs, however the major emphasis has been on applications like composites, hydrogen storage, electrochemical uses etc. [5]. CNTs as building blocks of movable machine parts is another major field [6] which needs to be explored.

The major machine elements which have been conceptualized at the nano-levels and are built using carbon nanotubes are springs [7-10], bearings [11-15], gears [16,17] and threaded elements [6,18]. Apart from these other related mechanical components have also been fabricated or proposed using carbon nanotubes. A summary of common mechanical elements built using carbon nanotubes is presented in Table 1.

Carbon nanotubes (Figure 1) have an interesting combination of properties that make them viable for machine elements [5]. CNTs have a lows inter shell co-efficient of friction [19,20] which make them suitable for rotational and sliding machine elements, primarily linear and rotational bearings [11,13-15]. Efforts have been made to accurately determine and study its dependence on factors like tube configuration and temperature [21] as well as pressure [22]. CNTs also have a high aspect ratio, high strength, high stiffness, low density which makes them suitable for a class of machine elements.

Figure 1: Single Wall Carbon Nanotube

Nanotubes have a very broad range of electronic, thermal, and structural properties that change depending on the different types of nanotube (defined by its diameter, length, and chirality, or twist). Besides having a single cylindrical wall, with nanotubes (SWNTs) one can have multiple wall nanotubes (MWNTs) -- cylinders inside other cylinders. As strength is one of the critical properties required by many mechanical elements, the following are the accepted values for the elastic properties of CNTs.

- Young's Modulus (SWNT) 1 TPa [35-39]
- Young's Modulus (MWNT) 1.28 TPa [37]
- Maximum Tensile Strength 30 GPa [40]

In this paper we look at possible applications of carbon nanotubes as machine elements. For each type of machine elements, we have discussed the suitability of carbon nanotube in terms if its strengths and weaknesses. Despite the progress, a lot of research is still needed to explore their possibilities for existing and newer applications.

No	Element	Type	Properties	Major issues	References
1	Linear Bearings	MWNT, 'Bamboo Configuration' [12]	• Controlled and reversible telescopic extension. • No wear or Fatigue.	Capped Ends as major hindrance	[11], [7], [13]
2	Linear Springs	MWNT SWNT	• High Mechanical Energy storage. • Controlled & reversible telescopic extension. • Large & reversible volume reduction due to crush & flattening of cross-section.		[7], [8]
3	Torsional Springs	MWNTs	• High Aspect Ratio Beams. • Chemically inert and no surface roughness.	Disordered form of coupling in MWNTs. Similar devices may be produced using SWNTs	[9], [23], [24]
4	Rotational Bearings	MWNTs, DWNTs	• Low Inter shell friction. No wear	Critical threshold exists for the maximum strain energy.	[14], [15]
5	Gears	MWNTs.	• High Young's Modulus • Electronic properties vary as a function of diameter and chirality	Work concentrated at simulation level.	[16], [17]
6	Conduits	SWNTs	• Structure of nanotubes.		[25]
7	Bolt/Nut Pair	DWNTs	• Potential relief analogous to a thread of a bolt		[6], [18]
8	Drive Shaft	MWNTs	• High Stiffness • High aspect ratio		[26]
9	Ropes	SWNTs	• Deformability of Cross-section. • High strength and Stiffness.	Larger diameter nanotubes are required.	[27], [28]
10	Tweezers	Two CNTs attached to electrode.	• Mechanical toughness • Electrical conductivity.	Used for mechanical manipulation and for electrical applications	[29]

Table 1: Carbon Nanotubes as Machine Elements

2 CARBON NANOTUBES AS MACHINE ELEMENTS

2.1 Springs and Bearings

Bearings and springs are by far the two most well understood carbon nanotube machine elements. It is now possible to make the layers of a MWNT slide over one another in a controlled fashion, thus leading to the fabrication of linear bearings and springs which are completely wear-free due to the extremely small friction force [7,11,13]. The springs formed from MWNTs are constant force springs. In a very similar fashion this low inter-shell friction can be utilized to make rotational bearings from DWNTs or MWNTs [14]. Thermal effects on these bearings have also been studied through molecular dynamics simulations at finite temperature.[15]

Applying pressure on the CNT material can also store mechanical energy. The density of CNT tends towards that of graphite on application of pressure because of flattening of tube cross-section. The reversible work done was found to be 0.18 eV/C atom and pressure at maximum compression was 29 Kbar [8].

Torsional springs have also been successfully made from carbon nanotubes [9,23,24]. The estimation torsional spring constant as well as shear moduli through controlled experiments has also been reported[23]. The inter-shell coupling force however is found to vary in MWNTs due to disordered bonds present in between layers. Thus there is a need to develop these devices by using SWNTs which are free from these defects [9].

2.2 Gears

If we bond rigid molecules like benzene to a carbon nanotube shaft by techniques such as Scanning Tunnel Microscopy (STM), it may be possible create nano-gears. [16] Currently research on this topic is limited to molecular dynamics simulations [17] but potential applications if successfully implemented are numerous. Ref. 16 also studies the chemical feasibility of bonding atoms to the shaft. Also presented are some processes to manufacture such a system. To run such a system we can place free positive and negative charges along the "gear teeth". These charges can easily be introduced through simple functional group substitution. Srivastava [17] has shown molecular dynamics simulations for such a system where a laser electric field is applied to generate motion.

2.3 Nut-Bolt Pair

An interesting observation in DWNTs is that they have a potential relief analogous to a thread of a bolt.[18] It has been proposed to use this property to generated nanotube devices which have linear as well as rotational motion between shells. Thus acting as a Nut and Bolt pair where the relative motion of the nanotube walls takes place along these "thread" lines.[6] The dynamics of such a motion have also been studied and some applications like nano-resistor and nano-drill have been proposed.[6]

2.4 Other Machine Elements

Besides the components discussed above, CNTs have also been proposed for use as other machine elements in nano mechanical systems not necessarily involving motions. These are conduits, drive shaft, ropes, tweezers etc. Nanotweezers developed are Nano Electro-Mechanical Systems (NEMS) for manipulation and interrogation of nanostructures. These nanotweezers are made of two carbon nanotube probes forming the arms of the tweezers [29]. Sub-micron clusters and nanowires were successfully grabbed and manipulated by these nanotweezers. Nanotubes are a good choice for construction of nanotweezers because they exhibit remarkable mechanical toughness and also electrical conductivity.

It has also been found that carbon Nanotubes can be used for transporting nano-materials, thus acting as conduits, by application of a voltage gradient [25]. Nano-ropes can be built from nanotubes and used for the purpose of load transfer.[28] This however is not a true mechanical machine element and should be dealt with in the field of composites.

3 SCOPE FOR FUTURE WORK

Some of the important barriers for realization of the true potential of carbon nanotubes are cost, polydispersity in nanotube type and limitations in processing and assembly. [5]. Attempts have been made to develop methods for continuous production [30]. Some element specific hindrances need to be worked upon.

There is an urgent need to model and simulate performance of carbon nanotube based machine elements considering mechanical, electros-static and electromechanical forces. The results of these simulations will pave the way for building nanomechanical systems purely based on carbon nanotubes.

Assembly and fabrication of nanomachines based on carbon nanotubes is another important issue which has not been dealt in the literature. Maintenance and environmental factors are crucial for successful realization of such machines which need to be addressed.

We plan to conceptualize, simulate and build complete mechanical systems using nanotubes. The work of modeling and simulation of carbon nanotube based machine elements is underway and results of which will be communicated in future.

REFERENCES

[1] Drexler K. E., "Nanosystems: Molecular Machinery, Manufacturing and Computation", New York: Wiley, 1992.

[2] S. Iijima, Nature 354, 56, 1991.

[3] DresselhausM S, Dresselhaus G and Avouris Ph, "Carbon Nanotube: Synthesis, Structure, Properties and Applications", Berlin: Springer, 2001.

[4] Dong Qian, Gregory J Wagner, and Wing Kam Liu, Min-Feng Yu, Rodney S Ruoff, "Mechanics of carbon nanotubes", Appl. Mech. Rev. 55, 495 (2002)

[5] Baughman et al., "Carbon Nanotubes--the Route Toward Applications," 297, 787-792, Science, 2002.

[6] Yu.E. Lozovik, AV.Minogin, AM.Popov, "Nanomachines Based on Carbon Nanotubes," Phys. Lett. A 313, No1-2, 112 – 121, 2003.

[7] A. Zettl and John Cumings, AIP Conference Proceedings Vol 544(1), 526-532. 2000.

[8] Chesnokov SA, Nalimova VA, Rinzler AG, Smalley RE, and Fischer JE, "Mechanical Energy storage in Carbon Nanotube Springs ," Phys. Rev. Lett., 82, 343–346, 1999.

[9] S. J. Papadakis, A. R. Hall, P.A.Williams, L. Vicci, M.R. Falvo, R. Superfine and S.Washburn, “Resonant Oscillators with Carbon-Nanotube Torsion Springs,” Phys. Rev. Lett., 93(14), 146101-1, 2004.

[10] Baughman et al., “Carbon Nanotube Actuators,”, Science, 284, 1340-1344, 1999.

[11] Cummings, J and Zettl, A., “Low friction nanoscale linear bearing realized from multiwall carbon nanotubes,” Science, 289, pp 602-204, 2000.

[12] Iijima S, Ajayan PM, Ichihashi T., “Growth model for carbon nanotubes,” Phys Rev Lett., 69(21), 3100-3103, 1992.

[13] A. Kolmogorov and V. H. Crespi, "The smoothest bearings: interlayer sliding in multiwalled carbon nanotubes," Phys. Rev. Lett., 85, 4727–4730, 2000.

[14] Bourlon B, Glattli DC, Miko C, et al., “Carbon nanotube based bearing for rotational motions”, Nano Letters, 4, 709-712, 2004.

[15] Sulin Zhang, Wing Kim Liu, and Rodney S. Ruoff
”Atomistic Simulations of Double-Walled Carbon Nanotubes (DWCNTs) as Rotational Bearings,” Nano Letters 4, 293-297, 2004.

[16] Han, J., Globus, A., Jaffe, R. and Deardorff, G., “Molecular dynamics simulations of carbon nanotube-based gears,” Nanotechnology, 8, 95-102, 1997.

[17] Srivastava, D. "A Phenomenological Model of the Rotation Dynamics of Carbon Nanotube Gears with Laser Electric Fields", Nanotechnology, 8, 186, 1997.

[18] R.Saito, R. Matsuo, T. Kimura, G. Dresselhaus, M.S. Dresselhaus, Chem. Phys. Lett., 348, 187, 2001.

[19] M.F. Yu, O. Lourie, M.J. Dyer, K. Moloni, R.S. Ruoff_, Science, 287, 5453, 637, 2000.

[20] M.F. Yu, B.I. Yakobson, R.S. Ruoff_, J. Phys. Chem. B 104, 37, 8764, 2000.

[21] J. Servantie, P. Gaspard, “Methods of Calculation of a Friction Coefficient: Application to Nanotubes,” Phys. Rev. Lett., 91(18), 185503-4, 2003.

[22] Xinling Ma, Hongtao Wang, and Wei Yang, “Tribological Behavior of Aligned Single-Walled Carbon Nanotubes,” Journal of Engineering Materials and Technology, 126, 258-264, 2004

[23] Williams PA, Papadakis S.J., Patel A.M, Falvo M.R., Washburn S, Superfine R., “Torsional response and stiffening of individual multi-walled carbon nanotubes,” Phys Rev Lett, 89(25), 255502, 2002.

[24] Williams, P.A., Papadakis, S.J. Patel, A.M.; Falvo, M.R. Washburn, S. Superfine, “Fabrication of nanometer-scale mechanical devices incorporating individual multiwalled carbon nanotubes as torsional springs,” R. Applied Physics Letters, 82, 805-807, 2003.

[25] B.C. Regan, S. Aloni, R.O. Ritchie, U. Dahmen, and A. Zettl, “Carbon nanotubes as nanoscale mass conveyors,” Nature, 428, 924-927, 2004.

[26] Jian-Min Li, “Fabrication of a carbon nanotube drive shaft component,” Nanotechnology, 15, 551-554, 2004.

[27] Jian Ping Lu, “Elastic Properties of Carbon Nanotubes and Nanoropes”, Phys. Rev. Lett. 79, 1297–1300, 1997.

[28] Dong Qian et. al., Composites Science and Technology, 63, 1561–1569, 2003.

[29] P. Kim, C. M. Lieber, “Nanotube Nanotweezers,” Science, 286, 2148, 1999.

[30] Ishigami et. al. Chemical Physics Letters 319, 457–459. 2000.

[31] Su C.J., Hwang D.W., Lin S.H., Jin B.Y. and Hwang L.P., “Self-organization of triple-stranded carbon nanoropes”

[33] Peter J. F. Harris. “Carbon Nanotubes and Related Structures: New Materials for the Twenty-First Century”

[34] M. Ishigami, John Cumings, A. Zettl, S. Chen “A simple method for the continuous production of carbon nanotubes”

[35] “Energetics, Structure, Mechanical and Vibrational Properties of Single Walled Carbon Nanotubes (SWNT)", Guanghua Gao, Tahir Cagin, William A. Goddard III

[36]"Young's Modulus of Single-Walled Nanotubes", E. Dujardin, T. W. Ebbesen, and A. Krishnan, P. N. Yianilos, M. M. J. Treacy,

[37] "Nanotubes: Mechanical and Spectroscopic Properties”. E. Hernández and Angel Rubio

[38]"Physics News Update, The American Institute of Physics Bulletin of Physics News, Number 279 (Story #2)", July 15, 1996, Phillip F. Schewe and Ben Stein.

[39] Lecture given at Michigan State University by Phaedon Avouris, a nanotube researcher at the IBM labs. [2000]

[40] Min-Feng Yu, Bradley S. Files, Sivaram Arepalli, Rodney S. Ruoff, Phys. Rev. Lett. 84, 5552 (2000).