THE NEED FOR 3D PRINTING OF AIRPLANE ELECTRIC MACHINES

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***Abstract* – With the symmetric circuit and control architecture of SYNCHRO-SYM with an "active" rotor assembly as the only exception,[1] all electric machine systems for electric airplane propulsion are actually the same century old asymmetric electric machine circuit and control architectures with a "passive" rotor assembly of permanent magnets, DC field windings, slip-induction windings, or reluctance saliencies that only achieve distinguishable performance enhancement by introducing refined selections of available (or futuristic) high performing material, winding, packaging, manufacturing, or electronic control techniques. Although attempted several times since its conception (circa 1950s), amorphous metal ribbon (or its nanocrystalline counterpart) has significantly better electromagnetic properties for electric machine cores than any electrical steel, but has never been successfully applied in an electric machine system because of extreme tool wear or worse, irreversible damage to its delicate magnetic properties with traditional methods of manufacturing the core slots and the precision flat air-gap surfaces. Although 3D Printing has been proposed as a solution, such as by ARPA-e,[2] empirical studies by Best Electric Machine show that MOTORPRINTER is the only practical 3D Printer concept in development for the additive manufacture of amorphous or nanocrystalline electric machine cores with integral frame and bearing assembly.**

***Index Terms*—brushless, real-time, sensor-less, synchronous, wound-rotor, doubly-fed, electronic power transformer**

I. INTRODUCTION

With the symmetric electric machine circuit and control architecture of SYNCHRO-SYM with an "active" rotor assembly as the only exception,[3] all of today's so-called new, advanced, or invented airplane electric machine systems are actually the same century old asymmetric electric machine circuit and control architectures with the asymmetry of a "passive" rotor assembly of reluctance saliencies, permanent magnets, DC field winding, or slip-induction windings, that only achieve distinguishable performance enhancement by introducing refined selections of available (or futuristic) high performing material, winding, packaging, electronic control, or manufacturing enabling techniques. For instance, development in high frequency electronic control for high speed electric machine systems are being pursued to reduce the size of the electric machine system and thereby, reducing the volume of preciously expensive rare-earth permanent magnets while seemingly disregarding the compounding size, cost, and inefficiency of the necessary but extraneous gearbox and high power, high frequency (HP-HF) magnetic cores for the electric machine, which includes the HP-HF transformer of the electronic controller. This brings us to the common understanding that "we need better magnetics," such as magnetic material, conductors, and insulation or enabling manufacturing techniques, such as 3D Printing.[4, 5] In response, Best Electric Machine is fabricating a patented additive manufacturing tool (or 3D Printer), called MOTORPRINTER, that additively manufactures HP-HF wound, axial flux, high electromagnetic performance amorphous metal (or nanocrystalline) ribbon electric machine cores with integral frame and bearing assembly.

II. PERFORMANCE ELECTRICAL STEEL RIBBON

Since its invention (circa 1950s), amorphous (or glass) metal ribbon has been a magnetic core material, such as electrical steel ribbon, with excellent high power and high frequency magnetic properties, such as high permeability, low hysteresis and core losses, and high flux density saturation limit. Although successful in utility power transformers, amorphous metal ribbon is seemingly impractical for electric machines because of extreme tool wear or damage to its delicate magnetic properties when forming the precision flat air-gap surface or the slots for holding the permanent magnets, reluctance saliencies, or windings with conventional manufacturing methods. But compared to electrical steel ribbon, amorphous metal ribbon retains the same structural strength but reduces core losses by at least 80% and increases core permeability by at least a factor of ten for reducing magnetizing MMF or the amount of expensive rare earth permanent magnet material and for providing narrower but deeper slots for smaller diameter electric machines. By annealing the amorphous metal ribbon core to a recrystallized state with extremely small, uniform grains, nanocrystalline metal ribbon, such as FINEMET, is a more recent advancement in electrical steel ribbon with much higher permeability, lower core loss, lower magnetostriction, and comparable flux density saturation than amorphous metal ribbon.[6]

Note: Because of the extreme difficulties of manufacturing amorphous metal ribbon electric machine cores, including electric transformer cores, with programmable shapes of precision slots and perfectly flat air-gap surfaces, an alternative is the 3D Printing of soft magnetic composite (SMC) material by a patented innovative method of sputtering layers of melted metal droplets (or grains) into a magnetic core shape that is enclosed in a sealed chamber of gas that deposits an oxidized coating of insulation on each grain. Like all SMC cores, the encompassing insulation layer on each grain does provide lower loss magnetic cores but detrimentally shows magnetic cores with very low magnetic permeability and structural strength, if compared to amorphous metal ribbon cores.

III. MOTORPRINTER CONCEPT OF OPERATION

MOTORPRINTER is the only practical additive manufacturing means for any family of high power, axial-flux electric machine cores, such as synchronous, asynchronous, reluctance electric motors, generators, and transformers, with amorphous or nano-crystalline metal ribbon, which is the strongest and highest performing HP-HF electromagnetic material available, and with integral frame and bearing assembly.

Note: Theoretical considerations by Polard showed the axial-flux (or adjacent rotor and stator disk form) electric machine reduces copper utilization by 13-14% and reduces iron utilization by 21.5-32.5% over a similarly rated but very common radial-flux (or cylinder inside a cylinder form) electric machine, while providing higher torque density and better fine adjustment control of the air-gap depth and without rotor and stator surface contention during speed.[7] Already, the axial-flux form is dominant for the electric vehicle traction motor market and should be dominant for electric airplane propulsion.

MOTORPRINTER follows the less common method of additive manufacturing (or 3D Printing), called laminated object manufacturing 3D Printing.[8] Accordingly but without providing other trade secret details, MOTORPRINTER builds the final form of the desired axial-flux electric machine magnetic core with any optimized slot shape by “adding” one thin layer of metal ribbon at a time, such as amorphous metal ribbon, with the shape template of the immediate layer removed by a laser cutter before layering on the previous layer of the axial-flux core with slots perfectly aligned into slot channels. Laser cutting the slot template on a single layer significantly reduces heat stress and damage to the electromagnetic properties of the ribbon. In contrast, today’s seemingly traditional means of 3D Printing deposits a thin layer of metal powder that is fused to the layered shape template of the final form by laser welding the metal powder of the immediate layer to the previous layer but any performance electromagnetic property of the powder material is destroyed by welding. Both methods show waste, such as the removal and reprocessing metal cuttings or the non-fused metal powder, but with a dramatic reduction in waste in comparison to the common subtractive manufacturing method that “removes” one layer of material at a time from an oversized bulk piece of encompassing material but preserving the properties of the bulk material.[9] Further, only the pre-manufactured raw material of MOTORPRINTER, such as amorphous metal ribbon, is inherently compatible with the electromagnetic properties of the magnetic core being manufactured, which is very different from pre-manufactured raw powder metal material of traditional 3D Printers that must be compatible with the operation of the 3D Printer instead of the desired properties of the core being produced. Unlike all other 3D Printers, the raw material for MOTORPRINTER is third party volume manufactured with the most optimized electromagnetic and structural properties, which are retained by MOTORPRINTER during the 3D Printing, and at the lowest cost possible.

After the core is additively manufactured, MOTORPRINTER automatically wraps the winding set by a laminated object manufacturing method of adding one winding-turn at a time, while coating each winding wrap (with epoxy or ceramic) to improve overall winding insulation and structure. During any annealing process to bring the additively wound amorphous metal core to a nanocrystalline state with a magnetic aligning current applied to the windings, the heated wires of the windings will naturally assume the air-gaps between windings, such as provided by square magnetic wire, and between the slot surfaces for the ideal densely packed winding arrangement.

IV. MOTORPRINTER PERFORMANCE ATTRIBUTES

Different from other Laminated Object Manufacturing 3D Printers, MOTORPRINTER comprises at least the following proprietary and trade secret attributes for manufacturing axial-flux electric machine cores:

- The layered core shape template with any desired slot or shape for holding permanent magnets, reluctance saliencies, or windings, is remotely, precisely, and dynamically cut on the next individual thin layer of ribbon before being wrapped onto the previous layer of the axial-flux core by a proprietary method that precisely and automatically aligns the cut slots of the axial-flux toroid without regard to the dynamically varying tolerances of ribbon thickness or core diameter, which would confuse any dynamic calculation method;
- Without discussing additional trade secrets or the empirical studies that were fully orchestrated by BEM with Metglas, an amorphous metal foundry, and several fiber laser cutter companies, such as IPG Photonics, the laser cutting on a single layer of ribbon controls heat stress to significantly reduce damage to the delicate material;
- The air-gap edge of the ribbon is forced to assume the precision flat airgap surface on each wrap to eliminate secondary tooling processes with extreme tool wear and material damage, such as Blanchard grinding;
- The robust frame and bearing bezel assembly of pre-manufactured structural stock, such as steel bar stock, composite stock, etc., is additively attached to the finished core;
- Pre-Manufactured raw materials are readily available from off-the-shelf material stock, such as amorphous metal ribbon, magnet wire, or building material, which are already performance pre-optimized at the molecular level under the most optimized, volume production with the lowest cost manufacturing processes.
- Empirical studies fully orchestrated by Best Electric Machine demonstrated high cutting speeds, which reasonably translates to scalable annual production rates of many thousands of axial-flux electric machines within a single MOTORPRINTER footprint of a standard shipping container;

- MOTORPRINTER will globally democratize the prototyping and manufacture of performance electric machines with the highest performance materials available for electric airplane propulsion.
- MOTORPRINTER additively manufactures high frequency transformer cores (PDF-HFT) within the wasted annulus space of the low frequency axial-flux SYNCHRO-SYM cores on the same frame and bearing bezel assembly for another level of power density for electric airplane propulsion.
- A computer aided design (CAD) tool, called BEM-CAD, was specifically developed to interface with MOTORPRINTER for the design and manufacture of axial-flux electric machines, including frame and thermo considerations;

V. CONCLUSION

Until MOTORPRINTER, there is no known implementation of a practical additive manufacturing technology for highly efficient amorphous or nanocrystalline metal ribbon axial-flux electric machine or high power, high frequency electric transformer cores, both of which are essential for the next level of electric airplane propulsion advancement.

[1] www.bestelectricmachine.com
[2] https://arpa-e.energy.gov/?q=slick-sheet-project/additive-manufacturing-electric-vehicle-motors
[3] www.bestelectricmachine.com
[4] Rober V. White, "We Need Better Magnetics," White Hot, IEEE Power Electronics Magazine, June, 2017, page 108 & 106.
[5] Ajay Misra, NASA Glenn Research Center, "Nano-Magnets and Additive Manufacturing For Electric Motors," 8th Annual CAFÉ Electric Aircraft Symposium, April 25-26, 2014
[6] https://www.hitachi-metals.co.jp/e/products/elec/tel/p02_21.html
[7] Zahra Nasiri-Gheidari, Hamid Lesani,"A Survey on Axial-flux Induction Motors," PRZEGLAD ELEKTROTECHNICZNY (Electrical Review), ISSN 0033-2097, R.88 NR 2/2012.
[8] Laminated Object Manufacturing 3D Printers
[9] "Automated Metal Powder Recovery System for the Additive Manufacturing Industry," Jan 4, 2018