Audio Engineering Society

Convention Paper 9060

Presented at the 136th Convention
2014 April 26–29 Berlin, Germany

This paper was peer-reviewed as a complete manuscript for presentation at this Convention. Additional papers may be obtained by sending request and remittance to Audio Engineering Society, 60 East 42nd Street, New York, New York 10165-2520, USA; also see www.aes.org. All rights reserved. Reproduction of this paper, or any portion thereof, is not permitted without direct permission from the Journal of the Audio Engineering Society.

A Novel Moving Magnet Linear Motor

Claudio Lastrucci[1]

[1] Powersoft S.p.A., Scandicci, Firenze, 50018, Italy
claudio.lastrucci@powersoft.it

ABSTRACT

Electrical to Acoustic conversion approach has not changed since the beginning of Acoustics.
New technologies in the electronic amplification domain and latest magnetic materials open a door in the field of alternative methods of acoustic transduction.
A new electrodynamic device that considerably improves electrical to acoustical conversion efficiency, sound quality, robustness and power handling, has been developed
A fully balanced and symmetrical moving magnet motor design, along with anysotropic magnetic compound integration, delivers substantial performances in terms of acceleration, linearity and efficiency, providing additional degrees of freedom in high quality professional speaker design.

1. BACKGROUND

Electro-dynamic transducers are based on a very well known technological approach that has existed for close to a century.
Some specific limitations in the amplification and trasducer matching have been driving the evolution of such devices down a very narrowed path , leading to a “single branch” technology that dominate the vastity of different application of acoustic reinforcement, the moving coil topology.
A couple of decades ago, a new method of amplification - the switch-mode output stage – arrived on the market and has been replacing the well-established linear amplification approach at an ever-increasing rate.
There are considerable of benefits provided by switch-mode amplification:
Efficiency, size, weight and the operational costs for a given power output and performance.
Beside the above features, a native property is the capability to drive extremely reactive loads while not being affected (as previous technologies), by catastrophic amounts of dissipated power. In the domain of power amplification language, a full four quadrant safe operating area (SOA) is a general property of a switch-mode amplification.
This grants an additional degree of freedom in the behaviour of the transducer to be matched and so

allows the exploration of different solutions from the ubiquitous moving coil approach.
A radically new electrodynamic transducer topology has been developed to take advantage of the unique properties of switch-mode amplification properties as well as the capabilities of modern magnetic materials.
Advanced electromechanical parameters, merging techniques that unify the amplification and transduction chain, expand the applicability of this new device even further.

2. MOTOR STRUCTURE

As with a conventional moving coil actuator, the forces are generated by current and magnetic field interaction, however the stationary reference have been moved from the magnet and yoke assembly to the exciting coils, which become the "heavy" part of the system.

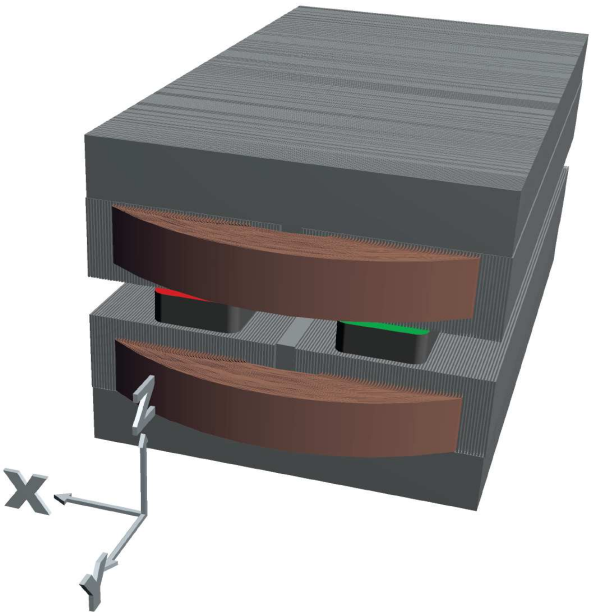

Figure 1 magnets and coils assembly

The active magnetical portion of the device is based on two parallel bars of NdFeB magnets, facing to a common plane but with opposed magnetic field orientation (orthogonally to the plane XY in Figure 1).

Two coils are placed facing the bars of magnet in a way to create a sandwich structure that holds the magnet within the coils.
The coils are wound using a ribbon of solid conductor, forming a winding of rectangular shape.
The magnetic field generated by the magnets is forced to cross the conductor of the coils, producing, once the coils are subjected to current, a relative force between the coils and the magnet bars.
This force linearly depends on the intensity of the field generated by the magnets and the current flowing into the coils.
To maintain a very low reluctance path for the magnetic field generated by the permanent magnets, a mix of conductive material such as copper or aluminium and ferromagnetic material such as Silicon Iron have been incorporated into the exciting coils. The ribbon of conductor have been interleaved with properly shaped sheets of low losses FeSi, in a way to create a high permeability path across the coil turns.
Notheworty that such designed coils present a very anisotropic magnetic behavior:
High permeability through the coil plane (XY) and a very low relative permeability (in the range of 2) in the transversal conductor direction (X direction).
An outer ferromagnetic shell has been implemented to allow easy circulation of the steady field generated by the magnet bars and to create a defined path for the variable flux produced by the current flowing in the coils.

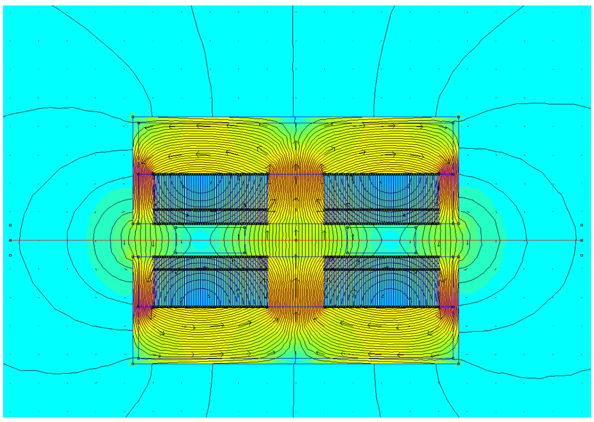

Figure 2 flux path in the cross section with 150A excitation, coils in series, no magnets inserted

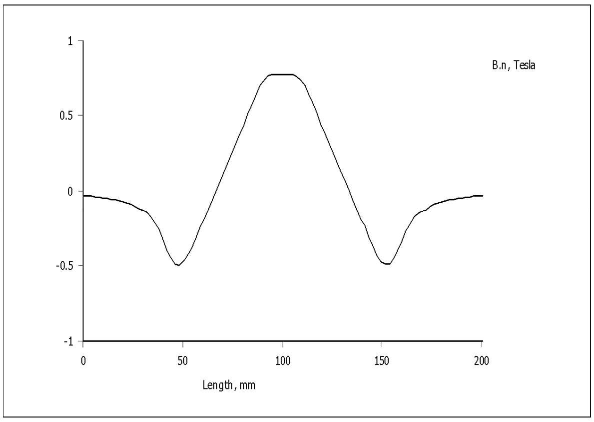

Figure 3 flux distribution along the gap (magnets plane) with 150A excitation, coils in series no magnets inserted

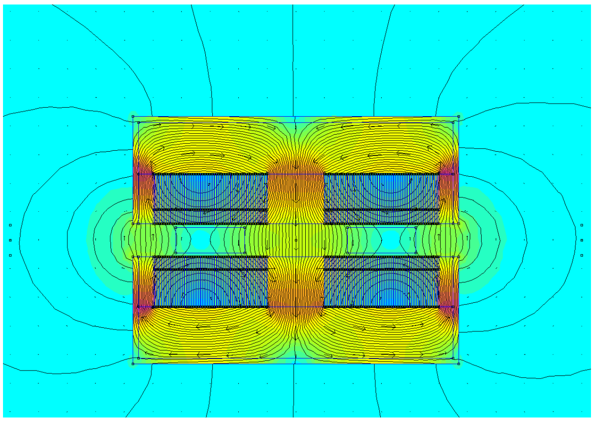

Figure 4 flux path in the cross section with -150A excitation, coils in series, no magnets inserted

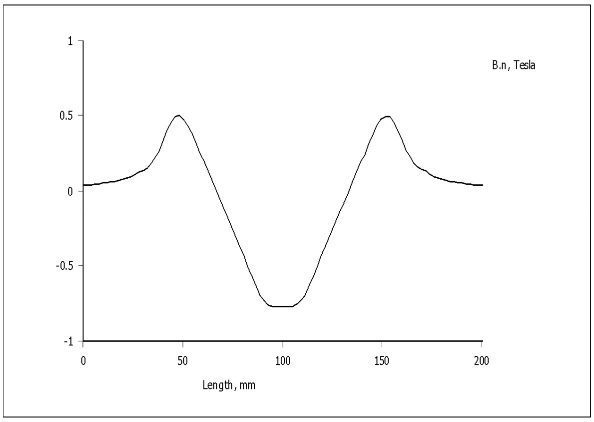

Figure 5 flux distribution along the gap (magnets plane) with -150A excitation, coils in series no magnets inserted

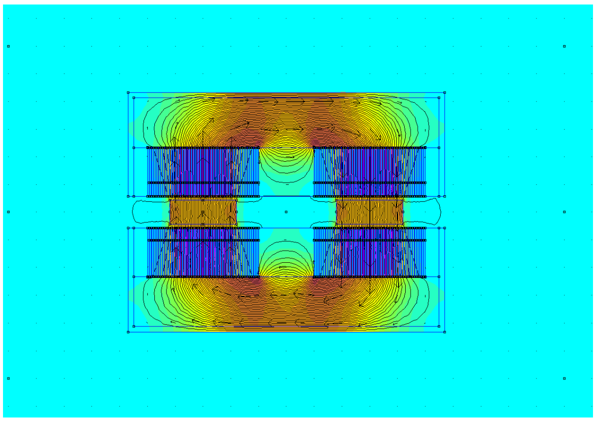

Figure 6 flux path in the cross section, magnets inserted and no excitation current into the coils.

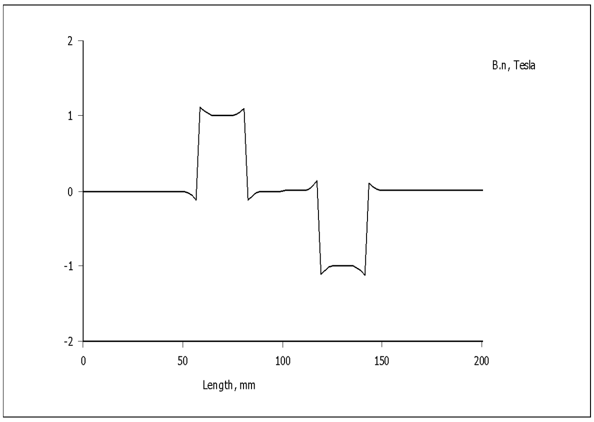

Figure 7 flux distribution along the gap (magnets plane) , magnets inserted and no excitation current into the coils.

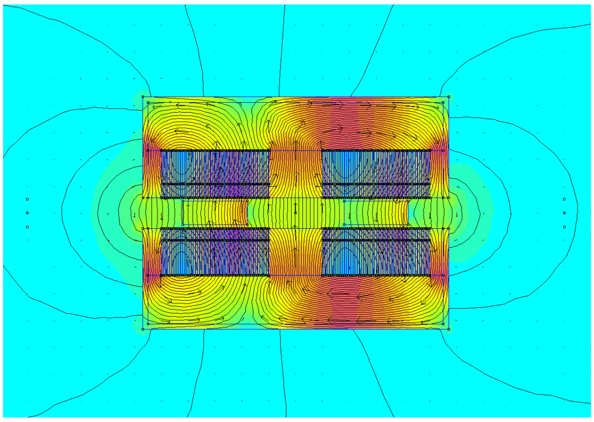

Figure 8 flux path in the cross section with 150A excitation, coils in series, magnets inserted

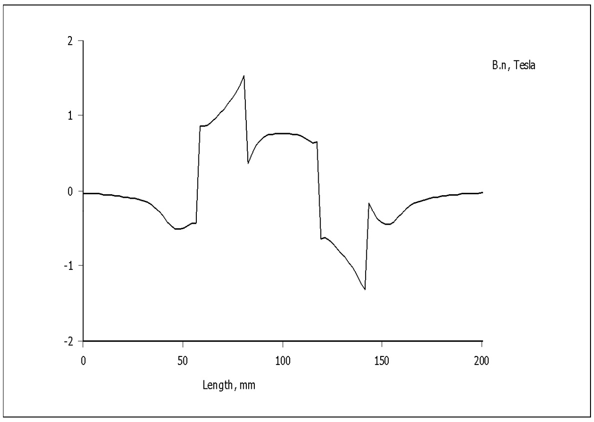

Figure 9 flux distribution along the gap (magnets plane) with 150A excitation, coils in series, magnets inserted

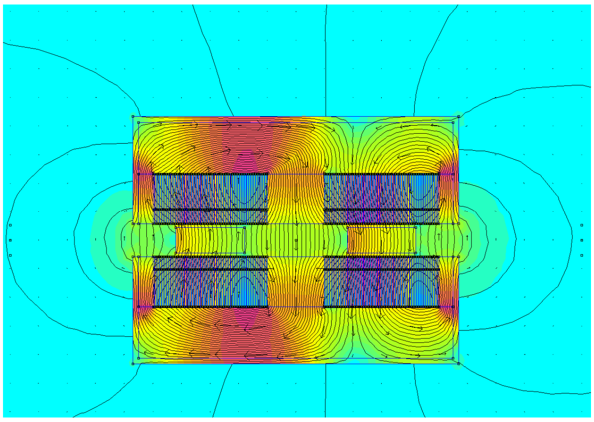

Figure 10 flux path in the cross section with -150A excitation, coils in series, magnets inserted

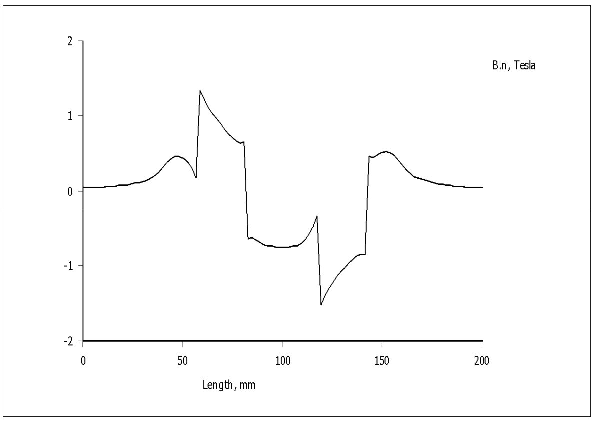

Figure 11 flux distribution along the gap (magnets plane) with -150A excitation, coils in series, magnets inserted

The magnets are positioned on a frame of composite material that provide a mechanical connection to the radiating part of the complete acoustical transducer.

Due to the natural symmetry of the device, this can be considered a real push pull device, where both magnet bars and coils work completely symmetrical in respect to the axial displacement and each portion of the conductors provide either push or pull action on each magnet bar in a complementary fashion to the other specular portion of the motor.

Being symmetrical in the X and Z directions, the resulting pulling forces from the magnets to the steady ferromagnetic structures are nulled out and, with proper magnet bar shaping, it is possible to achieve magnetic centering of the moving parts without the need of springs or suspension.

2.1. Motor Properties

The most evident feature of a moving magnet design is the absence of conductors in the moving portion of the motor.

The forces are provided by the interaction of the field that is generated by the steady coils and the field generated by the magnets that are not energized by any connection. With proper design, no eddy currents flows inside the magnets and the heat generated in the motor is due only by the I^2R losses in the coils conductor.

The absence of flexible conductors to the moving parts allows a free and very reliable operation even with extreme acceleration and displacement.

The stationary coils are built with very large cross section conductors, not having any constraints other than the cost of the conductor material and weight of the motor. These coils can be easily heatsinked and have at least one surface facing towards the outside of the device, allowing very low thermal to ambient resistance. Moreover, being built on large cross section and compounded with thermal filler, the motor does not show any hot spot behaviour. The thermal model is very simple and based on thermal capacity and thermal resistance of the entire device. Thermal Capacity, by construction is roughly two orders of magnitude more than that of a high power moving coil counterpart.

As a peculiarity, it is possible to increase the efficiency of the motor increasing the cross section of the conductor's coils without any loss of field, as the anisotropic behaviour of the compounded coils mantains the conductor cross reluctance constant against the width of the conductive ribbon.

This freedom of design provides a unique chance to reduce the coils resistance arbitrarily, whilst keeping the Bl value and the moving mass of the system unvaried. Verifications have been performed with devices that exhibit Motor Strength above 12,000 (Bl of 20N/m and coils resistance of 30 milliOhm).

The most challenging aspect regarding the performance of a moving magnet transducer is the capability to accelerate the "load" fast enough to provide the power bandwith for a certain application. The specific design of the coils and yoke allows the motor to achieve a Peak Force to Mass ratio of 6500N/Kg of magnet, over a linear displacement of 30 mm peak to peak. This level of displacement can be requested in extremely high SPL applications up to 100 Hz. Different sizing of the coils and magnets can increase the value that is, as with conventional moving coils, a trade-off between low frequency maximum output level and power bandwidth.

The limit of the Peak Force to Mass ratio also comes from the properties of the magnet material; highly coercitive materials with high Energy Product clearly deliver the best performances.

The trend of magnets performance envies a constant progress toward extremely high Energy Product compounds, improving the results even further.

The design of the yoke shape permits magnetic centering the moving parts and create a magnetic restoring system that acts in a similar fashion to mechanical springs.

The nature of any magnetic circuit seeking the lowest energy condition, allows geometric definition through the shape of the coils and the magnets, creating a pulling profile that recall the moving parts to the rest position.

An "end of stroke" unlinear behaviour of these magnetics springs can provide a steeper fall of compliance toward the extreme displacements condition, behaving as a gentle limiting action in the event of over excursion situations.

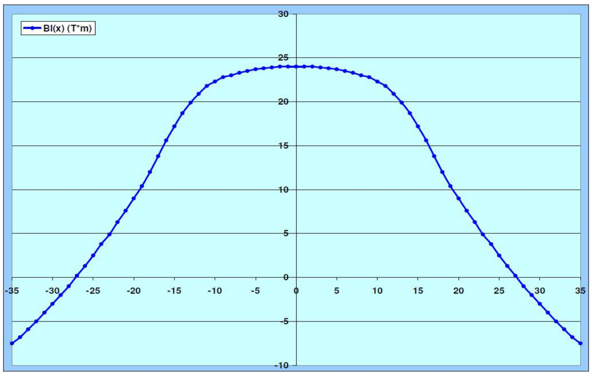

Figure 12 Motor Force Constant (Bl) Vs. position (N/A vs. millimiters)

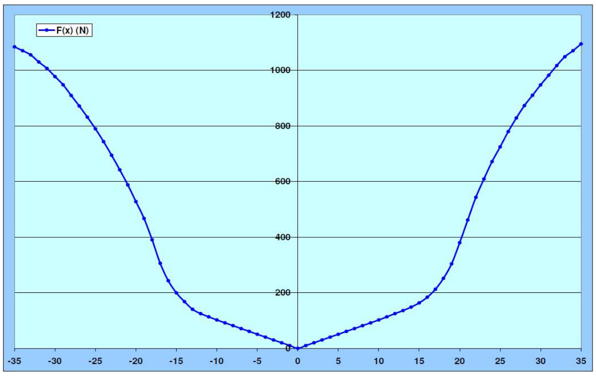

Figure 13 Springs Force Vs. position (Newton vs. millimiters)

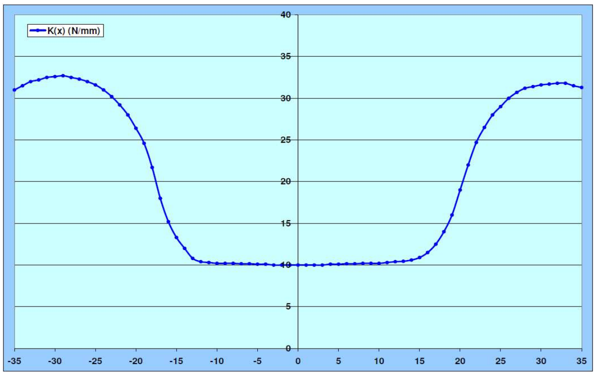

Figure 14 Springs Force Constant (K(x)) Vs. position (Newton/mm vs. millimiters)

The nature of the device, that involves large amount of ferromagnetic material biasing, leads to an unconventionally large inductance of the motor itself.
Given that the resistance of the coils is very low, the voltage demand of the device is - for a certain current and force requested - a linear function of the frequency.
Since the moving parts of the motor are not ferromagnetic (magnets have relative permeability close to 1), the reluctance of the overall assembly does not change with the displacement. Extremely low inductance modulation is one of the premium performances achieved. As a result, the inductance of the device is perfectly constant and linear versus the displacement and coil excitation.
The voltage and current relationship moves toward a pure inductor behaviour over the operational bandwidth, unless motional effects are taken in consideration. A free air impedance plot resembles a conventional moving coil transducer where the impedance rises at much steeper rate versus frequency.
This reactive behaviour sets a challenging operating condition for linear ouput stage amplification, but fits perfectly with a switch-mode output stage that, by topology, easily manage electrically displaced loads and large currents/low voltages demands and viceversa.

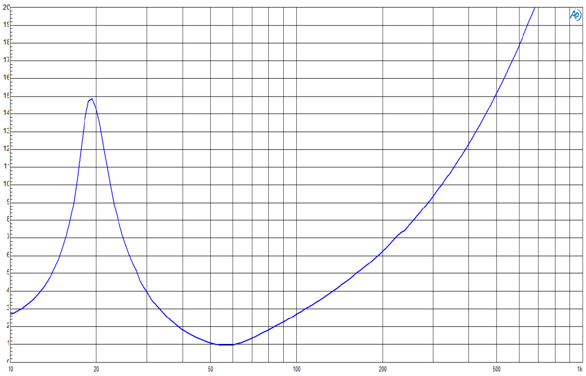

Figure 15 free air impedance curve motor only, no diaphragm (Ohm vs. Hz)

2.2. Performances

Despite the Thiele - Small parameters of the device are derivable with a combination of a radiating surface, in the electromechanical domain; it is easier to define the behaviour through the following set of data that belong to the motor only without any acoustical load.

<u>Electrical Parameters:</u>
Re = 0.260 Ohm
Le = 0.0059 H
Peak Current Handling = +/-170A
Peak Voltage Handling = +/-400V
Peak Power Handling = 25 KW

<u>Mechanical Parameters:</u>
Nominal Dimensions = 260x210x112 mm (body)
Weight = 21.5 Kg
Moving Mass = 0.950 Kg
Springs Compliance = 0.00007m/N
Mechanical Losses = 23 N.s/m
Resonance Frequency = 19.5 Hz
Linear Displacement = +/-15 mm
Maximum Displacement = +/-25 mm
Mechanical Peak Displacement = +/- 37 mm

<u>Electromechanical Parameters:</u>
Bl = 24.0 T.m
Motor Strength = 2,215 $(T.m)^2$/Ohm
Peak Force Output = +/- 4000 N

<u>Thermal Parameters:</u>
Thermal Resistance = 0.06 °C/W
Thermal Capacity = 11100 J/°C

3. DRIVE REQUIREMENTS

The low resistance value, the high Le / Re ratio and the consistent energy stored in the moving parts and compliances require a specific wide SOA driving amplifier. The output stage that provide the power to the transducer is required to deliver very high currents and voltages to exploit correctly the force capabilities. A drive unit has been developed specifically in order to fulfill the demands of the transducer. This amplifier module, beside having a voltage swing peaking up to +/- 300V and a current capability up to +/- 200A , provide a very short latency signal path through an on-board DSP, in order to accomplish the following unique matching features:

Programmable output impedance:
Resistive, actively synthesized values from -10 Ohm to +10 Ohm are selectable to change drastically the overall transducer model. This allows the reduction of the damping of the transducer, which can be necessary in a variety of acoustic designs.
Inductive, actively synthesized values from -2mH to +2mH are selectable to partially compensate the highly inductive behavior of the transducer.

Differential Pressure Control:
To create global feedback in the system that comprises the complete acoustic design in the loop, Differential Pressure Control detects, through a steady differential pressure sensor, the overall pressure acting on the radiating surface of the radiating diaphragm. This method allows the definition of a predictable behavior in the electrical – mechanical – acoustical signal chain, and allows reduction in the sensitivity of the system performance against aging and boundary condition. The Differential Pressure Control technique allows also synthesizing a wide range of Thiele - Small parameters for a given physical transducer [9, 12].

Protection and control:
All of the main parameters of the transducers are supervised; Voltage, Current, Power, Pressure, Displacement and Forces are maintained within the safety conditions and limited within a global amplifier and transducer combination.

Power Management:
To be able to maximize the performance of the transducer, a very effective energy recycling output stage has been designed which, together with the transducer efficiency, results in a considerable reduction in the size of the power supply. Power Factor Correction functionality integrated into the power supply further minimizes the overall mains current requirement.

Figure 16. Dedicated power module

4. APPLICATIONS

A typical application for the motor described above is low frequency acoustic generation. The nature of low distortion, high power handling and overall ruggedness, makes professional sound reinforcement the preferred field of use.
A specific radiating element has been developed to cope the high force and displacement provided by the motor. Large size vacuum formed conical polymeric diaphragms that embeds in a single material piece, the piston, the connecting elements and the outer surround as the load for the motor and the coupling device to the acoustical domain. The size of the diaphragm ranges from 22”, 30” and 40” for a maximum radiating surface up to 6500cm^2 (equivalent radiating surface of four 21” drivers).
A noteworthy point is that the extremely high motor strength of the device allows the low frequency cabinets to have a much smaller form factor for a given SPL performance and low-end extention.
Possible other fields of applications are: materials stress testing, vibrational active damping control, mechanical to electrical conversion, mechanical energy harvesting.

Figure 17 motor assembly with polymeric 30” diaphragm

5. CONCLUSIONS

A novel device that benefits from switch-mode amplification properties has been developed. The unique capabilities in terms of force, linearity, acceleration and ruggedness are the key features of the new device.
Extensive evaluation and performance comparisons have been run through measurement and listening tests.
The results have shown that the technology provides a real and in many ways superior alternative to conventional moving coil transducers with significant advantages in terms of power density, sound quality, reduced cabinet size and overall ruggedness.

6. REFERENCES

[1] L.L. Beranek, “*Acoustics*”, McGraw Hill 1954. Reprinted by American Institute of Physics, 1986.

[2] Karl Erik Stahl - “Synthesis of Loudspeaker Mechanical Parameters by Electrical Means: A new Method for controlling Low-Frequency Loudspeaker Behavior” – AES Journal, Vol. 29, September 1981

[3] W. Klippel, ”Loudspeaker Non Linearities - Symptoms, Parameters, Causes”, presented at the AES 119th Convention, New York, USA, 2005

[4] J. Danley, A. Rey, A high efficiency servo-motor driven subwoofer, Presented at the AES 74th Convention, October 8-12 1983 New York, USA

[5] Carlo Zuccatti, Thermal Parameters and PowerRatings of Loudspeakers, J. Audio Eng. Soc., Vol. 38, No. 1/2, 1990 January/February

[6] John Vanderkooy, Paul. M. Boers “High-Efficiency Direct-Radiator Loudspeaker Systems” AES 113TH Convention, Los Angeles, CA, USA, 2002 October 5–8

[7] Raymond J. Newman, D. B. (Don) Keele, Jr., David E. Carlson, Jim Long, Kent H. Frye, and Matthew S. Ruhlen “ An Important Aspect of Underhung Voice-Coils: A Technical Tribute to Ray Newman” Presented at the 121st Convention 2006 October 5–8 San Francisco, CA, USA

[8] Blasizzo, Desii, Di Cola, Lastrucci “ Practical applications of a Closed Feedback Loop Transducer system equipped with Differential Pressure Control” Presented at the 131st Convention 2011 October 20–23 New York, NY, USA

[9] John Vanderkooy, Paul. M. Boers and Ronald M. Aarts, “Direct-Radiator Loudspeaker Systems with High Bl”, J. Audio Eng. Soc., Vol. 51, No. 7/8, 2003 July/August

[10] D. B. (Don) Keele, Jr. “Comparison of Direct-Radiator Loudspeaker System Nominal Power Efficiency vs. True Efficiency with High-Bl Drivers”, Presented at the 115th Convention 2003 October 10–13 New York

[11] Claudio Lastrucci “Improvements to systems for acoustic diffusion” U.S Patent - US 8428278 B2

[12] Claudio Lastrucci “Electromechanical Conversion System with moving Magnets” U.S Patent Application - US 2013/0010999 A1