Design and testing of non-magnetic motors for MRI application

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Short abstract:
A typical Magnetic Resonance Imaging (MRI) environment is demanding due to high static magnetic field, high field gradients and high strength radio frequency fields. In addition, an MRI is a sensitive diagnostic tool that must not be affected by the components at the proximity of the imaging area, leading to artifacts in the diagnostic image of the scanner. Actuator solutions for usage in the MRI imaging area, in particular travelling wave piezo motors, are available commercially; however they present numerous drawbacks.
In this paper, a novel motor design based on the Piezo Actuator Drive (PAD) architecture is presented. It was tested in a Siemens 3T MRI. Results are presented and discussed. The results point that the motor can be used very close to the imaging volume without significant loss of performance and without affecting the medical diagnostic image

Keywords: Piezomotor, Non-magnetic, MRI

Introduction

There is a demand for MRI compatible actuators and motors, for example for instrumentation, in-scanner manipulation or haptics [1]. However a typical MRI environment is harsh due to high static magnetic field, high magnetic gradients and high strength radio frequency fields. In addition, an MRI is a sensitive medical diagnostic equipment that must not be affected by the artifacts arising from components at the proximity of the active imaging area. In the presented work, the following acceptability levels for MRI use have been set:

- Impact on image quality: The motor shall not induce a frequency shift of more than 0,25ppm when imaging a reference object (sphere of Ø240mm filled with oil).
- Susceptibility: The decrease in motor performance due to the magnetic field shall be less than 10%. In practice this is verified by measuring the torque generated by the motor driving a spring load
- Safety: For safety reasons, the static magnetic force generated on the motor placed at the entrance of the MRI bore shall be lower than 10% of its own mass. This can be measured by suspending the motor with a string and measuring the angle of the string

Motor solutions that are compatible with MRI environment, in particular travelling wave piezo motors [2], are available commercially; however they present drawbacks such as:

- Low torque and poor controllability at low speed, often requiring the use of additional gearing
- Limited lifetime (1000 hours) and deficient reliability
- Need for MRI-compatible sensor for closed-loop operation, leading to increased complexity
- Poor flexibility with regards to placement and size, due the tight integration between motor and controller electronics.

Other motor designs such as legged piezo motors [3] and pneumatic stepper motor [4] address some of these issues and provide excellent multi-imaging capabilities [5]. However for pneumatic and hydraulic motors the influence of hose length on performance and the relative complexity of the interconnection (in case the motor has to be moved from one MRI machine to another for example) will advantage the electrical options.
In this paper, a novel motor design based on the Piezo Actuator Drive (PAD) architecture is presented. Previous tests with that technology showed promising results [6], however the magnetic attraction force was still too high, due to the presence of magnetic stainless steel and a few other steel components. Adapted materials within a specific design improved greatly the MRI compatibility.

Material selection

Generally speaking, material selection is critical for MRI compatibility [7]. Studies have shown that only a limited number of materials are compatible, with a volume magnetic susceptibility in the range -20.10^{-6} to $+10.10^{-6}$ (unitless). Unfortunately few engineering materials are to find in this range, why very often is extended. With a magnetic susceptibility around 10^{-1}, even the best austenitic stainless steels, with very low magnetic permeability, can be utilized in very limited quantities.

The motors developed in this project make use of titanium ($1,82.10^{-4}$), copper ($-9,63.10^{-6}$) and polymers in addition to the multilayer piezo actuators.

The material selection was made as a trade-off between MRI compatibility and formability. In particular the manufacture of the microgear central to the PAD principle was of concern.

Motor design

- The PAD principle

In the PAD principle, two sets of actuators are used to generate a circular translational movement in the X-Y plane. This “wobbling” movement is converted into a rotation through a microgear [8].

- Low power motor

For this project, several prototypes were built and tested. A small motor was designed and manufactured, making use of machined PEEK and high performance bending actuators. The dimensions (excluding shaft) are 28,6x28,6x15,5mm (picture below).

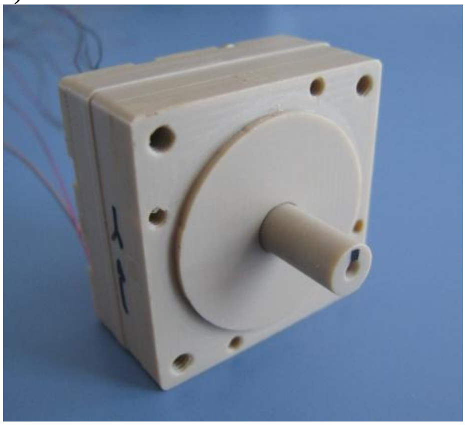


Fig. 1: *Low-power PAD prototype*

When designing a piezo-based solution, stiffness is a critical parameter. In the case of that low power motor using bending actuators, due to the amplification through the bending motion, the apparent stiffness of the actuators is in the range of 10 to 100N/mm. Therefore, relatively compliant materials such as polymers can be used in the design.

- High power motor

On the other hand for a high power motor using piezo stack actuators (10 to 100N/µm), plastics are excluded due to their low Young’s modulus.

For this project, a design was produced making use of titanium and copper alloys only.

The design includes four piezo stacks protected by a polymer casing, arranged in a “diamond” configuration. By driving the stacks by pairs in a push-pull configuration, it is possible to create the desired X-Y movement.

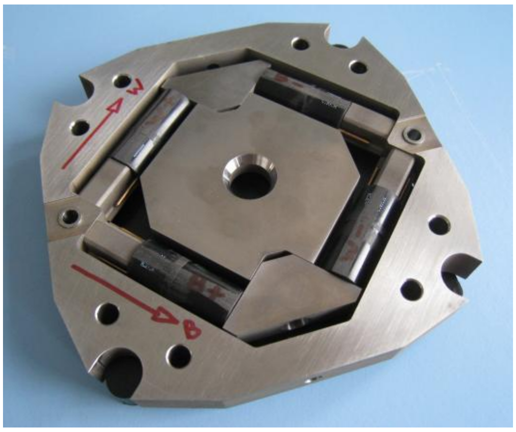


Fig. 2: *Internal components of the high-power PAD prototype*

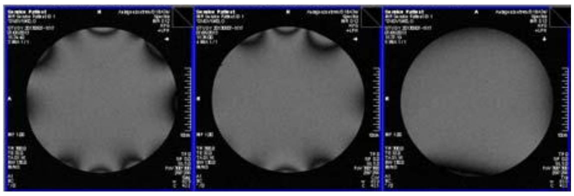
The fully assembled motor is (excluding shaft) 120x120x17mm.

Static imaging test results

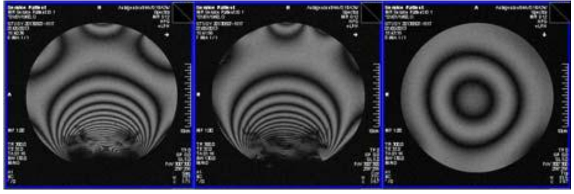
- Material tests

In order to validate the material choice for the high power motor, a first series of tests was conducted in a commercial Siemens 3 Tesla field MRI scanner. The test involved two sets of representative mechanical parts (motor housing, bearings, piezo elements), one in titanium, the other in “non-magnetic” stainless steel (1.4301 or AISI304).

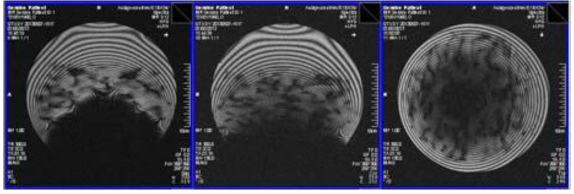
MRI scans are shown below. They indicate that titanium parts can be used very close to the imaging volume (20cm from the center) without affecting the diagnostic images quality noticeably, while the stainless steel parts have to be placed over 30cm away.



a: *Reference item*



b: *Titanium at 15 cm distance from center*



c: *Stainless steel at 15 cm distance from center*

Fig. 3: *Imaging results – one black/white transition represents a frequency shift of 0,25ppm which is the acceptability limit*

- High-power motor tests

Building on these preliminary results, a functional motor was assembled using titanium parts. The imaging quality test was reproduced with the final geometry (setup shown on picture below).

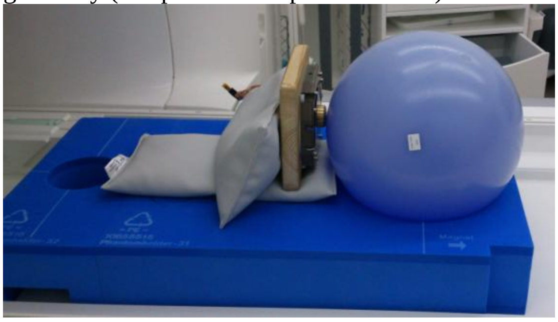


Fig. 4: *Setup for imaging tests*

The blue sphere is a reference item (phantom) for imaging. In that test, the motor is fixed on a wooden plate for easier manipulation and placed right against the phantom, corresponding to a distance of 14cm to the centre of the imaging volume.

The figure below compares imaging results depending on the distance between the motor and the phantom.

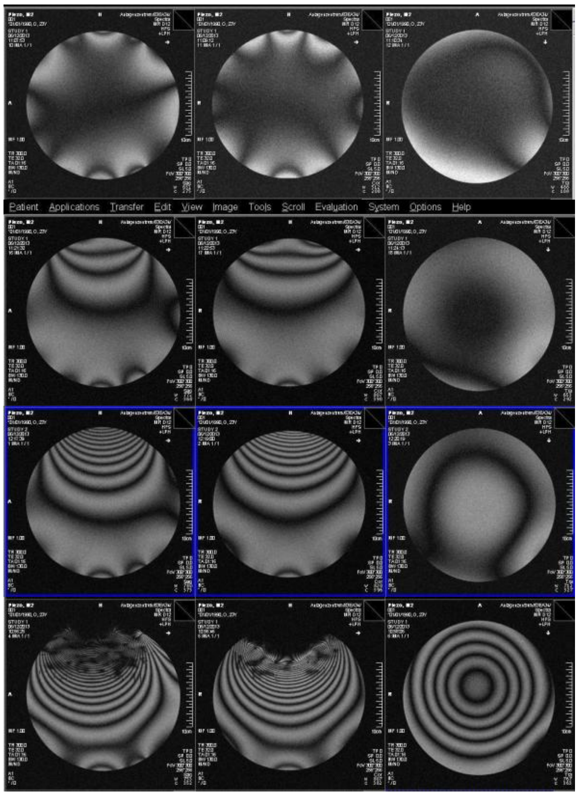


Fig. 5: *Imaging results – from top:*
Reference item (no motor)
Motor at 27 cm from centre
Motor at 22cm from centre
Motor at 14cm from centre

Although the impact of the motor is clearly visible, results become acceptable at a distance of 22cm from the centre.

These results confirm the preliminary tests on materials, although it can be noticed that a few centimeters were “lost” due to the more massive parts compared to the initial test.

- Low-power motor tests

A similar test was performed with the low power motor. MRI scans are shown below and indicate acceptable results even when the motor is directly placed against the phantom.

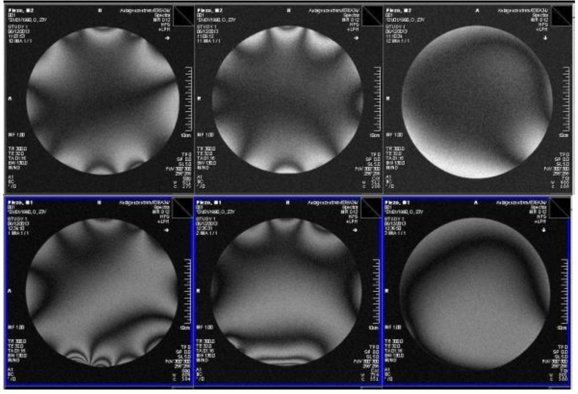


Fig. 6: *Imaging results – top: reference*
Bottom: motor at 14cm

The better results of that configuration can be attributed to two effects: the smaller dimensions of the motor and the more adapted magnetic susceptibility of the materials.

Functional test results

- Image quality (motor active)

It is important that the low impact on the imaging quality is also present when the motor is operating. In a further test both the low-power and the high-power motor were driven at low speed using a modified driver NDR8210 during imaging. Because this driver is not originally developed for operation in MRI environment, it was installed in the control room just next to the MRI room, connected to the motor through 8m of cabling and a filter.

As shown below for the high-power motor, operating induces very little change, under 0,25ppm frequency shift.

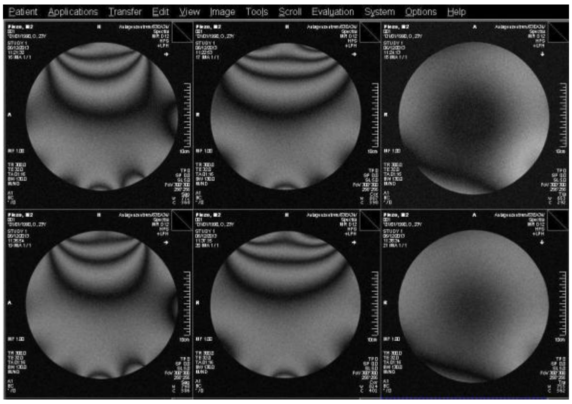


Fig. 7: *Imaging results*
Top: motor at 27cm from centre, not operating
Bottom: motor at 27cm from centre, operating

- Susceptibility

The torque capability of the low power motor was evaluated against a spring load while the MRI was active. The difference in performance is very small, within the measurement uncertainty.

As expected, the very low magnetic forces induced on the stator do not affect operation.

Conclusions and further work

In this paper, two motor designs are presented. Tests indicate that they are both compatible with MRI “zone 2” environment, i.e. for use at a short distance from the imaging volume. The best results are obtained with a polymer structure, however due to the low stiffness, this option is limited to low power (<1W) motors. Higher power (>1W) can be obtained with a titanium structure. The PAD principle presents several advantages that are relevant for MRI use: simple 4-wire interface; open-loop positioning; failsafe (normally blocked).

Further work includes refinements of the motor design to achieve a more compact and more powerful solution, as well as driver development for operation in the MRI environment.

Acknowledgement

The work presented in this paper is supported by the Danish National Advanced Technology Foundation.

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