Dynamics on an Electromagnetic Tilting Actuator in a Hyper Redundant Serial Chain

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ABSTRACT

A hyper-redundant serial chain concept based on bistable, electromagnetic tilting actuators for use in future endoscopic applications was proposed earlier. The dynamics modelling and the simulation of the tilting behaviour is essential due to different reasons: As the system is not equipped with any sensors, necessary power-on durations for driving the electromagnetic actuators from one tilting position to the other must be predicted. These durations can be calculated through the dynamics model with respect to acting forces and inertia. Additionally, power-on durations can be used to prohibit unintended opening of other actuators in the serial chain. Therefore, this paper focuses on the validity of the dynamic model of one actuator within the manipulator, through detailed measurements of its tilting behaviour with regard to different power-on durations.

1 INTRODUCTION

Endoscopic examinations have become a common tool in medical interventions as well as industrial applications. However, commonly used systems are either dexterous to withstand manipulation forces or flexible enough to manoeuvre in curved and contorted places [1], [2]. Improved systems should provide both: good adaption to curved paths is needed to achieve less deviation as well as to prevent looping and stress of the surroundings. Additionally, stiffness with respect to manipulation forces allows for moving in hollow spaces and interaction with the environment, without unintended movements of the endoscope tip.

In this context, different approaches have been proposed in literature. [1] and [3] give a very detailed overview on various ideas. However, proposed systems are in many cases subject to restrictions, such as limited flexibility, low resistance to manipulation forces, complex mechanical concepts, or non-linear kinematics.

Therefore, the authors proposed an active shaft concept based on binary, electromagnetic tilting actuators in [4]. The system features a simple, modular structure. It is based on a serial chain concept of equally one degree-of-freedom (DOF) electromagnetic tilting actuators. Thanks to its actuation concept, the system achieves high holding torques and, thus, provides high stiffness with respect to manipulation forces. At the same time, it can actively follow a curved path, without stressing surroundings. The serial chain can easily change its shape through the change of different actuator configurations. Therefore, the actuators are excited through a capacity discharge.

In comparison to the authors’ previous work [4]-[7], this paper focuses on the dynamics of one exemplary tilting actuator in the serial chain. The system behaviour with respect to different power-on durations (POD) is evaluated. For every change of the shaft’s shape, different PODs – describing the length of the capacitive discharge to excite the coils of the actuator– need to be determined. The hyper-redundant manipulator is not equipped with any sensors, neither to determine the whole serial chain configuration nor to control a single tilting process. Hence, the PODs need to be predicted using the dynamics model. Besides ensuring the actuator tilting, the PODs are utilized to reduce required holding torques: Even though the system is stiff with respect to external forces, its holding torque is limited due to the actuator and power electronics design. To guarantee appropriate holding torques, the impulsive contact forces, when reaching one of the bistable tilting positions, must be reduced. Among others, this is possible through optimized PODs to reach minimal impact velocities.

The remainder of this paper is organized as follows: for the sake of completeness, the system design is described first. Then, the modelling of the dynamics is derived. The model is compared with subsequently presented experimental evaluation in the next step.

2 SYSTEM DESIGN

To meet the outlined requirements for an improved system combining dexterity with good path-following capability, a binary actuated snake-like robot has been proposed in [5]. For better understanding, the key features are presented roughly in this section.

2.1 ELECTROMAGNETIC TILTING ACTUATOR

The electromagnetic tilting actuator (ETA) [4] acts similar to common electromagnets. However, it shows significant differences to solenoids' functional principles [8]. Two similarly built halves represent one actuator element (Fig. 1(a)). Each half consists of a kidney-shaped coil located inside a bevelled iron core. The sides of each half are electromagnetically segregated through paramagnetic joints, see Fig. 1**Fehler! Verweisquelle konnte nicht gefunden werden.**(b). Four cores build the ETA with a tilting range of $\pm\frac{q_{\max}}{2}$. An ETA has one DOF and tilts from left to right and backwards. The tilting torque is caused by Maxwell's boundary forces at the air-gap side surfaces.

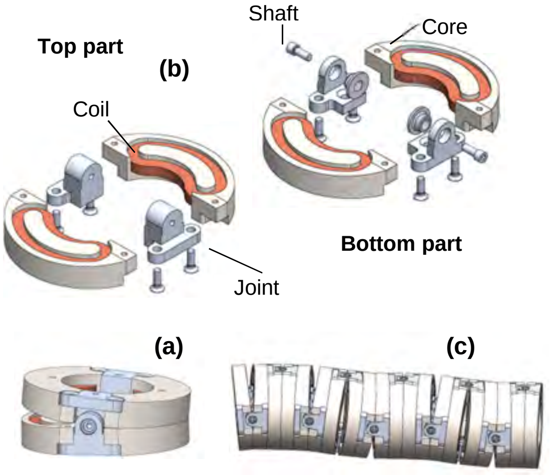

Fig. 1 (a) CAD model of one ETA, (b) exploded view of its components, (c) fully actuated shaft with twisted actuators [9]

The excitation for tilting is achieved with a capacitive discharge in the actuator coils, i. e. by a very high tilting current pulse with limited POD, see [9]. The capacitive discharge concept was chosen to prohibit thermal destruction through failures in switches or control. The capacitor load level is designed to be variable within the range of extra low voltage ($< 50\ \mathrm{V}$). After the tilting impulse, the actuator coils on the active side are supplied with a stationary thermally allowable DC holding current at an application dependent voltage of $2 - 5\ \mathrm{V}$.

The ETAs used for the measurements presented in this paper feature steel cores made from St37 without remarkable electromagnetic properties. In future, ETAs with the high-tech core material VacoFlux© will be used which is characterized by its high permeability and high saturation flux density.

2.2 SERIAL CHAIN CONCEPT

As shown in Fig. 1**(**c), the snake-like robot is a serial chain consisting of equally built ETAs. Even though each actuator offers only one DOF, quasi-continuous movements of the chain can be achieved through an appropriate arrangement of a large number of actuators. This necessitates a hyper-redundant design of the shaft. Details of the serial chain design and its kinematics can be found in [5].

3 DYNAMIC MODEL

The dynamical behaviour of the whole actuator chain highly depends on the properties of the single actuators. Therefore, the following section focuses on the dynamic model of an ETA. Then the model is expanded to consider the whole chain.

3.1 DYNAMICS MODEL OF SINGLE ACTUATORS

The ETA torque τ is mainly characterized by its magnetic circuit which determines the magnetic flux density B at the air-gap side surfaces. The flux density is excited by the current $i(t)$ inside the coils, see [9]. The excitation is provided by an oscillation circuit.

In [7] the simplified electromagnetic model was described. It is used to deduce the available driving torque for the following measurements. The model considers the static non-linearity and the capacity discharge current $i(t)$ and is based on the solution of the differential equation for the oscillating circuit and a $\tau - I - q$ map, gained from 3D finite element analysis. This simplified method neglects self-induced voltage, temperature changes, and dynamic non-linearity by eddy currents. After the terminable excitation, the model directly switches to holding current mode, compare sec 2.1.

3.2 SERIAL CHAIN MODEL

In general, the snake-like robot can be described through rigid body dynamics approaches, such as iterative, recursive Newton-Euler or Lagrangian mechanics [10]. However, as the number of simultaneously switching actuators is limited, simplified analogous models with a reduced number of DOF can be defined and parameterized as proposed in [7].

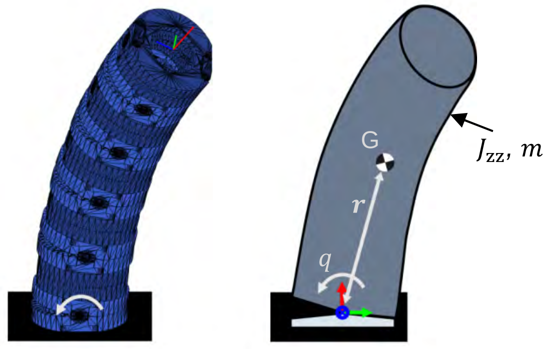

Fig. 220 Simplified dynamics model for one DOF

This paper focuses on the tilting of one exemplary actuator. Hence, the non-switching actuators can be combined to one rigid body with one resulting inertia J_{zz}, mass m, and centre of gravity G (see Fig. 2*Fig. 220*). For this setup, the dynamics equation with respect to the tilting angle q can be rewritten as follows:

$$J_{zz}\,\ddot{q} = m\,g\,r_y(q) + \tau(q), \tag{1}$$

where $\tau(q)$ is the actuator driving torque and $r_y(q)$ describes the y component of the vector $\boldsymbol{r}$ from the tilting axis to the centre of gravity. It is important to note, that this distance and the actuator torque are both subject to changes of q during the tilting process.

4 EXPERIMENTAL EVALUATION

For experimental evaluation of the dynamics model with respect to PODs, measurements are exemplarily conducted for one actuator and for different shaft configurations.

4.1 EXPERIMENTAL SETUP

The prototype of the snake-like manipulator is shown in Fig. 3*Fig.* . It is a serial chain consisting of ten actuators, each twisted by $90\,°$. Up to ten ETAs can be supplied through a power electronics board, which is controlled with a Simulink real-time environment running at 1 kHz. During experiments, the end effector movement is recorded using a Qualisys Oqus 4 high-speed optical tracking system with $2\,\mathrm{kHz}$ frame rate and an achievable accuracy of $0.1\ \mathrm{mm}$. Additionally, current and voltage are measured for every tilting procedure at supply input of the board and coil output.

Fig. 3 Prototype for experimental evaluation

4.2 EVALUATION OF THE ELECTRIC CIRCUIT

Whenever an actuator does not tilt but hold, only switch S_2 is closed (see Fig. 4*Fig.*). In this case the coils on the active side of the actuator (R_c and L_c) are supplied by $U_{q,h}$ with a DC holding current of about $i_h = 2\ \mathrm{A}$. To tilt an actuator, S_1 is closed and the capacities C_b and C_{ext} discharge into the coils. The capacities are loaded by the source $U_{q,t}$, which is limited to a comparably small current of $i_{q,t,max} = 3\ \mathrm{A}$. The principle circuit for excitation of one actuator is exemplarily shown in Fig 4*Fig.* (see [9]). The board has an integrated capacity of $C_b = 40\ \mathrm{mF}$ consisting of 20 capacitors distributed at the circuit board's bottom. For convenience, all board resistances are combined to $R_{b,t}$ in the tilting circuit and $R_{b,h}$ respectively.

The components are designed to safely operate with a tilting voltage up to $U_{q,t,max} = 48\ \mathrm{V}$. The overall capacity is extended to $C_{ext+b} = 304\ \mathrm{mF}$ with an external capacity. The value of C is to preserve the actuator coils in case of a failure.

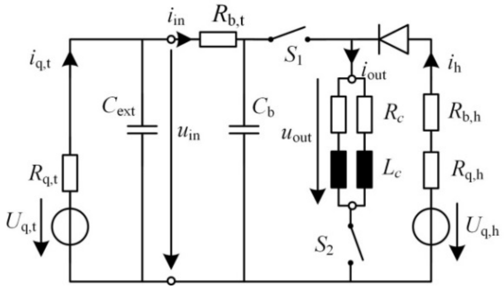

Fig. 4 Principal electric circuit

Due to actual board design insufficiencies, especially regarding the unevenly distributed board capacities, the measured electric curves cannot be calculated precisely with simulation models. These difficulties become obvious by taking a closer look at the exemplary tilting procedure with a POD of $20\,\mathrm{ms}$, shown in Fig. 5.

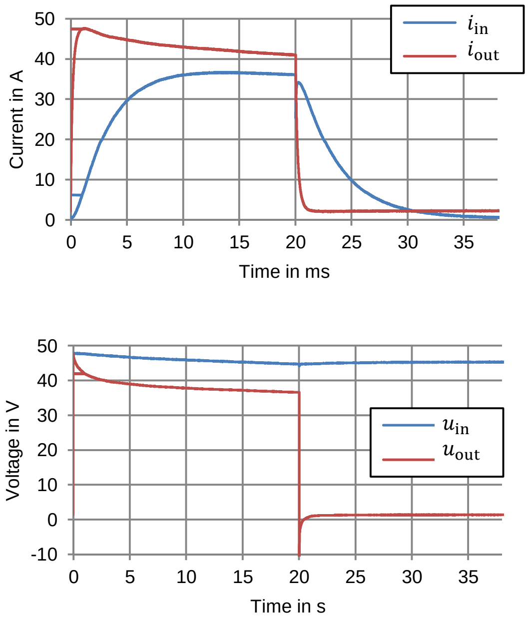

Fig. 5 Typical current and voltage slopes for the used board

The increasing current within the first $3\,\mathrm{ms}$ is mainly fed by C_{b}. Subsequently, the coils supply voltage (output voltage of the board) differs quickly from the input voltage of the board (equivalent to the voltage over the external capacity C_{ext}), as C_{ext} cannot unload with the same time constant due to the additional board resistance. After about $10\,\mathrm{ms}$, the external capacity current is fully available and mainly feeds the output current. Only the minimal gap between input and output current is still driven by the board's distributed capacities. After switch-off at $20\ \mathrm{ms}$, the output current decreases exponentially within $\tau_{\mathrm{elt}} = 0.6\,\mathrm{ms}$. This descent has still an influence on the actuators torque. At the same time, the board input current i_{in} only decreases slowly. As it balances the distributed and external capacities to the same load the capacities are again reloaded to U_{q}.

Therefore, the aforementioned point is not part of this publication.

4.3 EVALUATION OF TILTING BEHAVIOUR

For evaluation reasons, the tilting movement of the actuator at the base is measured with different PODs (see Fig. 6*Fig. 6*) for three different serial chain configurations (see Fig. 7*Fig.*), varying in terms of acting inertia and centre of gravity. With the help of the kinematics model [5],[7], the spatial end effector movement can be transferred into a tilting around one single axis.

Config.	Power-on durations in ms							
1	1	2	5	10	15	20	25	30
	35	38	40	41	42	44	46	48
	50	52	54	56	58	60	62	64
	66	68	70	72	80	90		
2	1	2	5	10	11	12	13	14
	15	30	45	50	70	80		
3	1	2	5	10	20	40	60	80

Fig. 6 Examined PODs

Fig. 7 Configurations 1, 2, 3 (left to right) for evaluation of the tilting procedures with respect to different PODs

4.3.1 Configuration 1

The evaluation of different tilting processes for configuration 1 with variation of the PODs is presented in Fig 8. The results show that due to the position of the COG, a minimal POD of $41\ \mathrm{ms}$ is necessary to finish the tilting process successfully (see Fig. 8①). If the minimal POD is not achieved, the actuator starts to tilt, but the provided torque is not sufficient to overcome the gravitational influence. Additionally, the results show that the longer the system is excited, the more the actuator opens until it returns to its initial position (see Fig. 8*Fig.*②). When the POD exceeds $68\ \mathrm{ms}$, impact forces during closing force other actuators in the serial chain to open unintendedly (see Fig. 8③) –

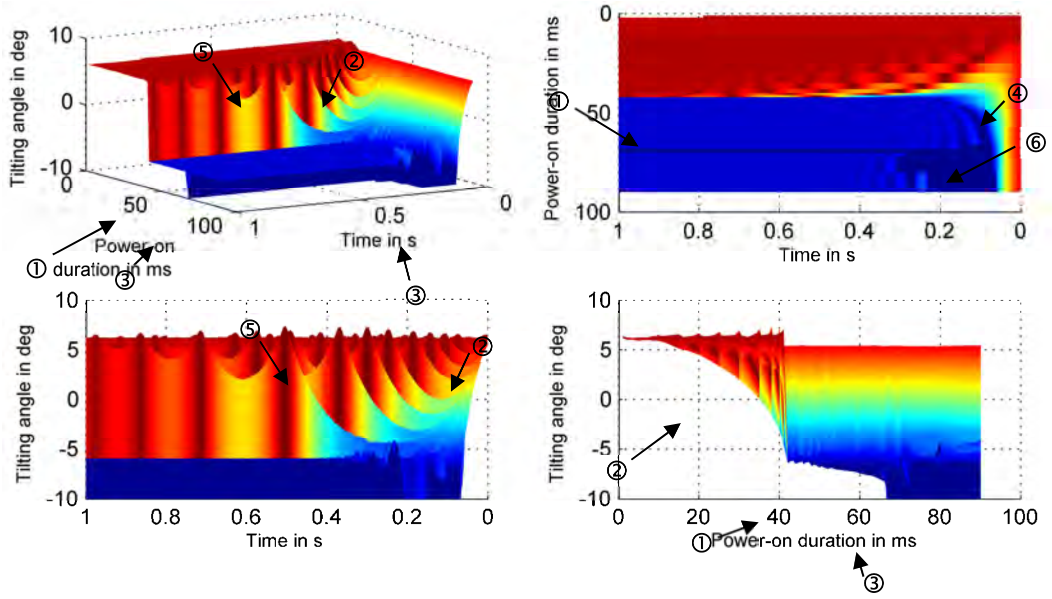

Fig.8 Results for configuration 1: tilting angle over time with respect to different power-on durations in different perspectives

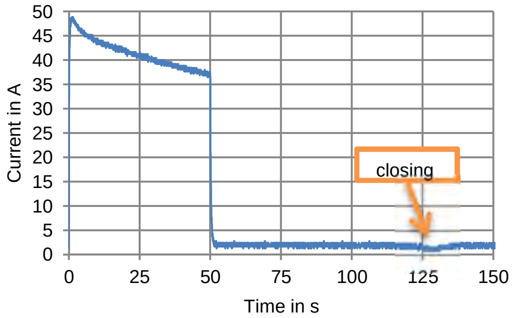

Fig. 9 ETA current and tilting effects for a POD of $50\ ms$

in this case the assumption of a one DOF system is not valid anymore.

Fig. 10 compares the experimentally identified tilting behaviour with the simulated one using the dynamic model. It is notable that the simulated map reproduces the measured tilting procedures despite of the simplifications very well, see e.g. Fig. 10①. However, there is a disparity between the minimally necessary tilting times (see Fig. 10②). In simulation, a POD of $49\ \mathrm{ms}$ is necessary for a successful change of the configuration. This means that the model overestimates the necessary excitation time by $+8\ \mathrm{ms}$. As the measurements permit a span of possible PODs, this offset is within an allowable tolerance. Reasons for the model deviation might be inaccuracies in the identified parameters (see [7]), in the modelling of the holding torques, or rather the transition between the torque models for holding and driving.

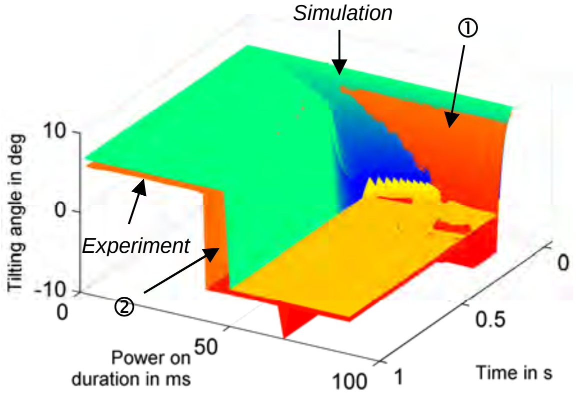

Fig. 10 Comparison between simulated and measured tilting behaviour

4.3.2 Configurations 2 and 3

To evaluate the influence of different inertias and different centre of gravities, the tilting is recorded for two further configurations (see Fig. 7*Fig.*). Configuration 2 is characterized by a nearly upright position of the serial chain. In contrast, in configuration 3 gravitational forces lead to a complete tilting into the desired configuration.

Power-on duration	Configuration			
	2		3	
	Sim.	Exp.	Sim.	Exp.
Necessary	8 ms	11 ms	0 ms	1 ms

Fig. 11 Necessary PODs for different configurations (simulation and experimental results)

The results for these configurations are shown in Fig 12*Fig.* and Fig. 13, necessary PODs from measurement and simulation are extracted in Fig. 11.

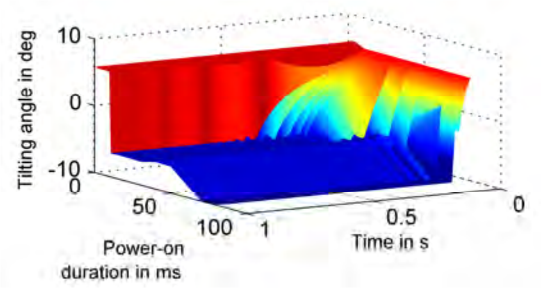

Fig. 12 Measured tilting behaviour for configuration 2

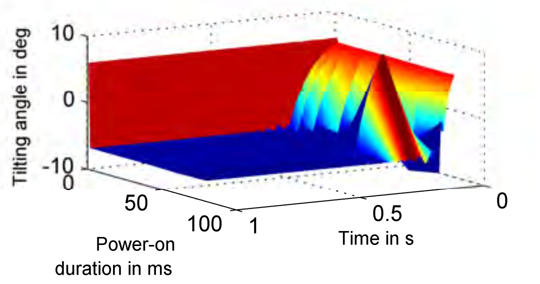

Fig. 13 Measured tilting behaviour for configuration 3

The results correlate with the already observed behaviour and the corresponding dynamic model. Again spans of possible PODs for a successful tilting process are clearly visible in both measurements. If the POD exceeds a certain time, some actuators change their position unintentionally. Compared to configuration 1, the minimally necessary PODs decrease, as the gravitational forces do not prevent the actuator from tilting. For configuration 3, only 1 ms of excitation is needed to tilt the actuator, even though it would tilt without excitation in the simulation. This is caused by a lack of static friction and residual magnetism in the dynamic model. In contrast to the results for configuration 1, necessary excitation durations are underestimated – even though the accuracy is higher in general.

5 CONCLUSION

In this paper, the dynamics modelling of the tilting behaviour of one single actuator was evaluated with respect to different PODs as well as to different shaft configurations. It was shown that the behaviour predicted by the dynamic model can reflect the experimentally obtained tilting behaviour well. All observed effects can be interpreted. Therefore, the actuator behaviour is comprehensible. Anyhow, a considerable difference in minimally necessary PODs indicates inaccuracies in the model. These could be reduced through a more in-depth parameter identification (see [7]) for a broaden model to cover not yet considered effect. However, a more embraced identification method requires more measurements for each actuator, which is not appropriate for large serial chains. Additionally, the tilting process can be modelled appropriately for the POD. Hence, modelling of the applied holding torques with respect to the joint angle can be a considerable influencing factor for the tilting behaviour with small PODs. Including this idea into the dynamics model is part of future work. Furthermore, next steps cover the experimental evaluation for other actuators, the consideration of temperature influences and the model-based determination of PODs.

6 ACKNOWLEDGMENT

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