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eBrake® – the mechatronic wedge brake

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ABSTRACT

eBrake® (1, 2) - a new "brake-by-wire" technology, was developed at the German Aerospace Centre, DLR e.V.. It is based on an electric powered controlled friction brake with high self-reinforcement capability. To avoid jamming the brake a special control technology was developed. Thus, by intelligently controlling a brake wedge, the kinetic energy of a vehicle is transformed into braking power. Furthermore an advanced design was found to deal with a broad variation of the friction coefficient. The physical effects involved lead to a significant reduction of energy consumption of the brake actuator compared to “conventional” brake-by-wire systems.

INTRODUCTION

The development work done on the "brake-by-wire" technology by the DLR based on the principle of a purely electromechanical braking systems corresponds fully with the general trend to replace, where and whenever possible, hydraulic or pneumatic systems with a clean and intelligent controllable electromechanical or mechatronic system. Mechatronic systems will most definitely become far more common and will penetrate all areas of the future industrial world and service industry and will represent a majority of the most innovative products in the future. Their importance for the economy in general will increase steadily during the next few years. The fields which will mainly profit from this development are the automobile and aircraft industry, fields which in the future will be much more dependent on export and international competitiveness (current examples for competition: ICE-TGV, Airbus-Boeing).
This integration of mechanical and electronic elements, as well as information technology (i.e. computer capacity) in order to create intelligent, controllable systems and machines will be replacing the classical standards of mechanical engineering in ever increasing fields and will eventually lead to a renaissance hereof with a new character. This integration often has to be achieved within a very small space – often within the scope of micro systems engineering. The optimal functionality of mechatronic systems can only be achieved by optimally combining electronics, information technology and mechanic elements into one system which works as a whole.
Already today there exist quite a few examples of mechatronic systems: CD players, ink jet-printers, tool machines as well as robots belong to this group just as "fly-by-wire“ planes do, or furthermore, ABS-, TCS- and ESP systems in cars, airbags which recognize the weight on respective seats, etc. The scope of applications will increase significantly in the future.

PROBLEM DESCRIPTION

The increasing requirements a modern braking system has to meet today – i.e. anti-lock braking systems, driving stability control systems, traction control systems – make wheel-selective braking necessary. To date, it has been possible to meet these requirements with conventional braking systems, which have been continuously upgraded by adding hydraulic pumps or magnetic valves. All of these solutions have however resulted in vibration, resonance and damping problems within the hydraulic pipes and difficulties in addressing the hydraulic module accumulator or in other words, the magnetic valves. Due to the characteristics of these magnetic valves, which are highly non-linear two-step controls, the possibility of achieving high control quality regarding the braking pressure is also rather limited.
All attempts so far to develop an electrical driven brake face the seemingly insuperable obstacle of extremely high actuator forces and the resulting high energy requirement of the actuator. The energy source, usually electric motors which have to supply quite significant torques and power, are large, heavy and accordingly expensive. For this reason a successful and profitable “all electric” brake-by-wire concept has not yet been developed.

NEW SOLUTION APPROACHES

The new DLR "brake-by-wire" technology is based on an electric powered controlled friction brake with high self-reinforcement capability (eBrake ®).
Whenever engineers deploy existing forces elegantly, usually the simplest concept is the most convincing. By intelligently controlling a brake wedge, the kinetic energy (momentum) of a vehicle is transformed into braking power.

MECHANICAL MODEL

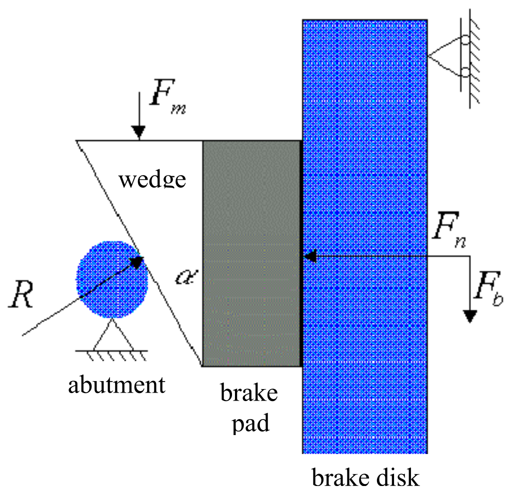

Fig.1: Mechanical Model

The brake lining is equipped with a wedge on its backside which is rested on an abutment, e.g. a bolt (Fig. 2). The actuator presses the brake lining in between the abutment and the brake disc with the motor force F_m. The braking force F_b resulting from the contact between the brake disc and the brake lining acts in the same direction as the motor force which results in the anticipated self-reinforcement.

From the force balance can be derived

$$F_m = F_b \frac{\tan\alpha - \mu}{\mu},$$

for the characteristic brake factor C* then applies:

$$C^* = \frac{F_b}{F_m} = \frac{2\mu}{\tan\alpha - \mu}$$

CONTROL SYSTEM AND FIRST TESTING

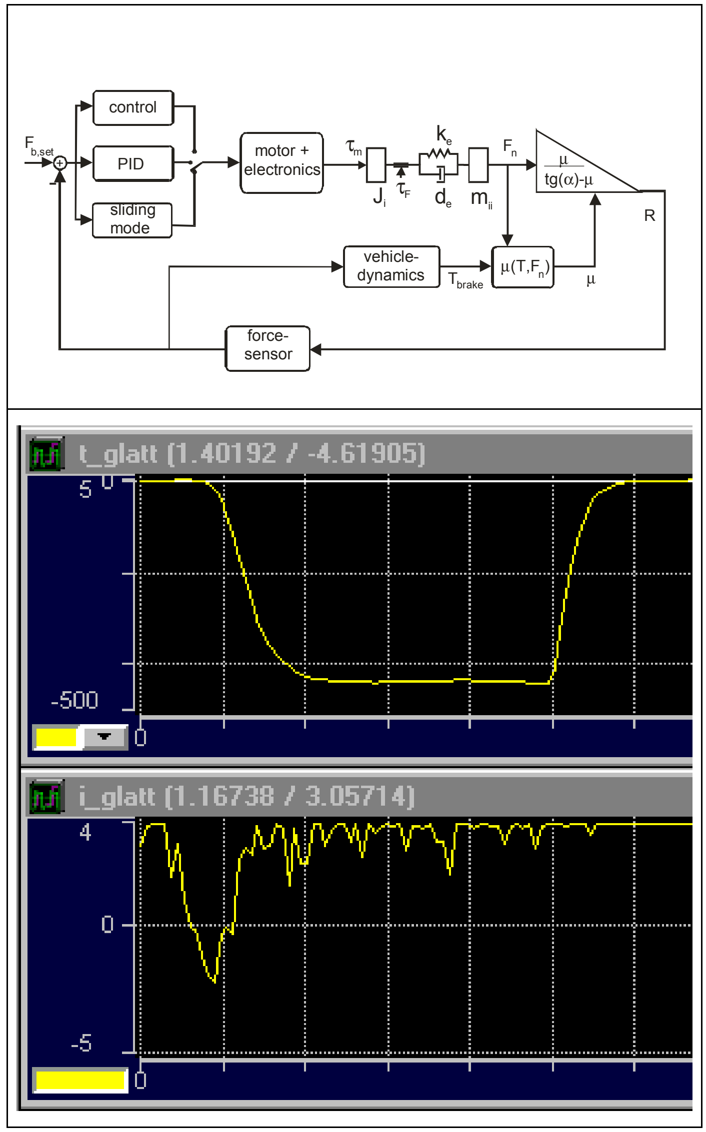

Fig.2: Control structure and braking test proving stability

The main problem with this simple but very efficient method of braking was to find a way to avoid the jamming of the brake or better said, to "control" this jamming advantageously. DLR was successful in solving this problem. A special control technology developed under Matlab/Simulink and dSPACE stops the wedge from getting stuck.
In order to prove the general concept of a controlled wedge brake a prototype of DLR eBrake® and a test bench was build (fig.3). In this first approach a stable ring construction was realized avoiding elasticity problems within the mechanical structure. Fig.2 shows the control structure and a braking test at 440 Nm braking moment proving stability of the system (see also 3). At this point it has to be said that due to restricted testing facilities the maximum braking torque of the set-up was limited to 500 Nm.

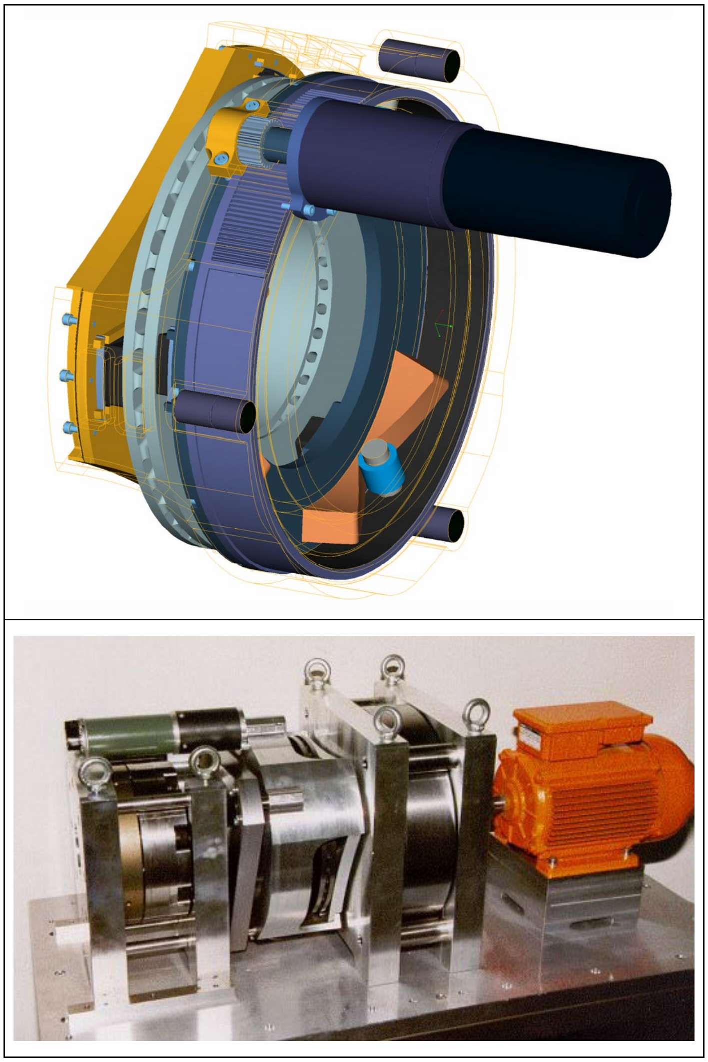

Fig.2: First Prototype of DLR eBrake ® and test bench

THE “PUSH-WEDGE” PRINCIPLE

Let’s have a look at the so called “push-wedge” principle (Fig. 4), meaning $\tan\alpha > \mu$.

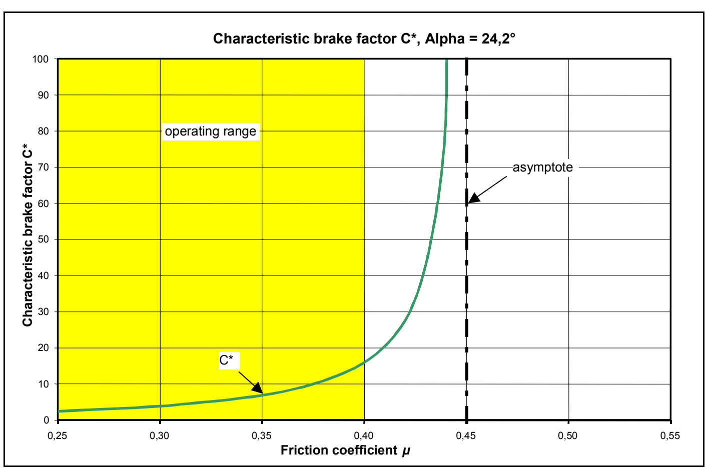

Fig. 4: Characteristic brake factor C* in relationship with the friction coefficient μ for a “push-wedge” principle.

In order to avoid jamming of the wedge the operating range has to stay well fond of the asymptote which is characterized by the condition $\mu = \tan\alpha$.

This requires a design with big wedge angles corresponding with low over all self-reinforcement capability. In this first approach to avoid the jamming problem it was thought, that reaching the critical point, i.e. the asymptote, during brake operation will cause the worst case, i.e. a complete blockage or even destruction of the brake. In reality this problem does not occur – but why?

THE “PUSH-PULL-WEDGE” PRINCIPLE

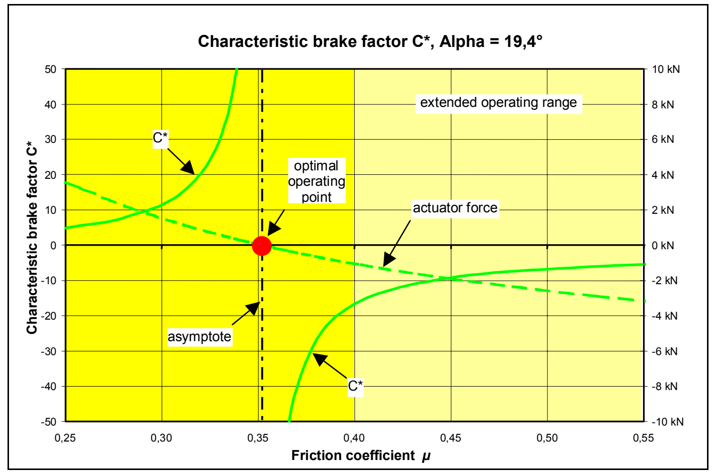

Fig.5: Characteristic brake factor C* in relationship with the friction coefficient μ for a “push-pull-wedge” principle.

In a real set-up the actuator, e.g. a motor+ spindle unit, is designed to deliver thrust and pull forces anyway. This is essential for a stable and fast control of the system, as there are bi-directional dynamic loads due to inertia within the power train itself. Looking at an increasing friction factor, e.g. during brake operation with rising temperature of the friction material, we reach a said critical point. But here the actuator force, i.e. the motor force, doesn’t become infinite – it becomes zero (Fig.5)! Once the friction coefficient rises further, the force direction within the power train will change from pushing to pulling. This means the actuator has to hold resp. pull the wedge out. Looking at the graph of the actuator force in fig.5 it becomes obvious that this said critical point is the most effective operating point of all: the self-reinforcement reaches infinity!

FURTHER WEDGE SHAPE OPTIMIZATION

Let’s for a moment suppose that the coefficient of friction would be constant and $\alpha = \arctan(\mu)$. In that case only a position control of the wedge would be necessary.

The position of the wedge corresponds with a defined widening of the elastic caliper leading to

$$F_n = c \cdot \tan(\alpha) \cdot x \,,$$

with the caliper stiffness *c* and the wedge position *x*. This means that the normal force is a function of the wedge position.
Following this idea we come to the first important insight how to reduce necessary maximum actuator forces in an overall approach:

<u>The wedge position corresponds to a defined normal force!</u>

Looking at the demanded maximum value for the braking force and taking into account the variation of the friction coefficient:

$$F_{b,\max} = \mu \cdot F_n = const.$$

then it becomes obvious that the maximum deflection of the wedge also depends on the friction coefficient:

$$x = \frac{F_{b,\max}}{\mu \cdot c \cdot \tan(\alpha) \cdot}$$

meaning that large deflections are only necessary when the coefficient of friction is low, e.g. due to fading. We conclude:

<u>The wedge angle for extreme wedge positions can be independently optimized for each value of the friction coefficient!</u>

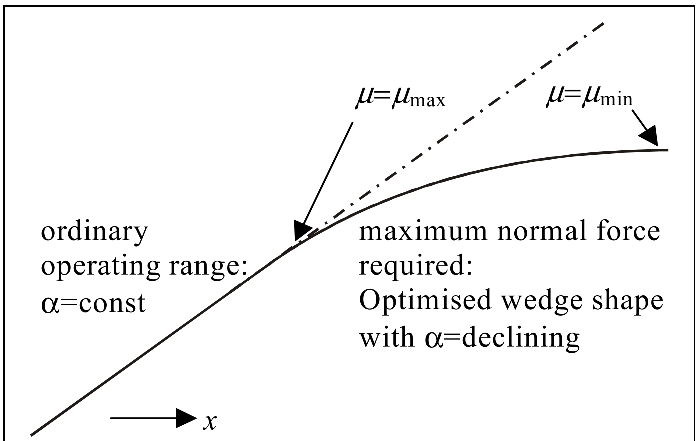

Fig.6: Optimized wedge shape meeting maximum normal force requirements with minimized actuator force.

This second insight leads to future potential for wedge shape optimization with declining wedge angle over increasing wedge deflection (Fig.6). Therefore the power train design can be further downsized.

ADVANTAGES OF THE EBRAKE®-CONCEPT

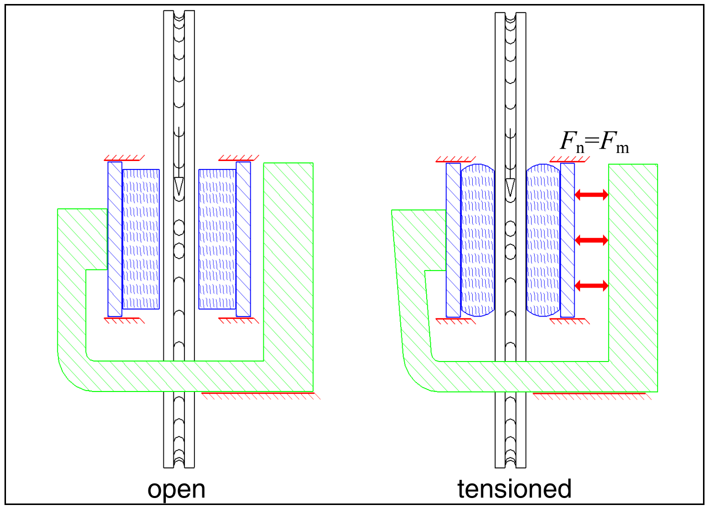

Fig.7a): Conventional braking philosophy

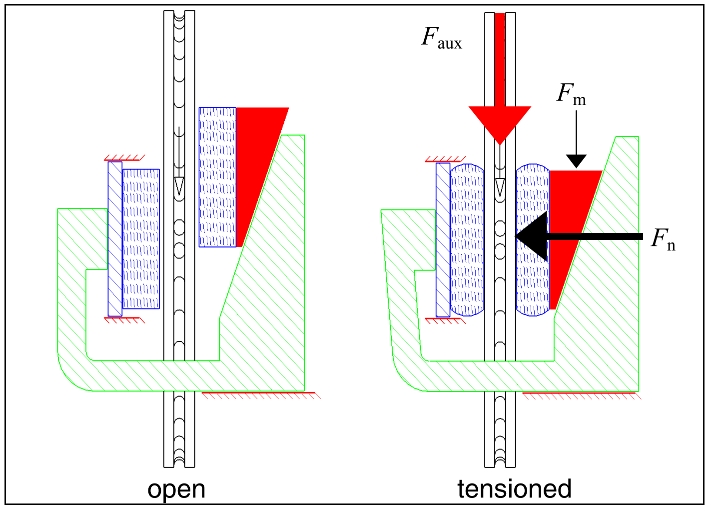

Fig.7b): eBrake® – electric powered controlled friction brake with mechanical self-reinforcement (4)

The conventional braking philosophy (fig.7a) assumes that the normal force has to be build up directly, actively and in full height. New concepts merely try to replace hydraulic or pneumatic brake units with electro-hydraulic, electro-pneumatic or all electric powered solutions. Talking about an all electric brake-by-wire approach the electric motor has to build up the full normal force. Furthermore the actuator has to supply the energy absorbed by resp. stored within the elastic caliper. Therefore an extremely high energy need for the braking actuator arises. Even further capacities have to be supplied in order to guarantee high system dynamics looking at high inertia within the power train. To achieve these goals large, heavy and expensive electric actuators, spindle units or gears have to be used leading to increased space requirements and increased primary damped masses within the chassis.
Instead the DLR eBrake® uses the vehicle's momentum to support the electric actuator (fig.7b). An auxiliary force derived from the self-reinforcement effect is used to build

up the normal force. Therefore the braking actuator only has to supply a small portion of the required normal force. Furthermore the energy needed to widen the caliper is also taken from the vehicle's kinetic energy.

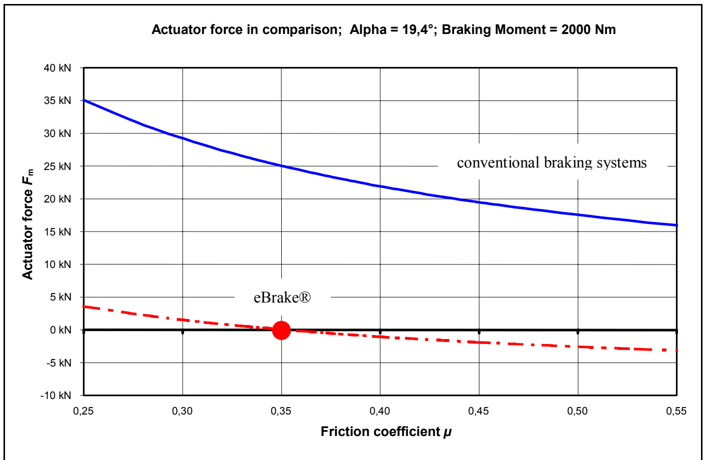

Fig.8: Braking power in comparison

The physical effects involved lead to the following advantages as opposed to "conventional" braking system in general and brake-by-wire systems in particular:

1. The average energy consumption of the actuator can be significantly reduced, because
   - the required actuator forces drop dramatically – down to zero in the optimal operating point (fig.8)
   - the energy needed to widen the caliper has not be supplied by the electrical supply system – it is taken from the kinetic energy of the vehicle
2. The actuator can be enormously downsized, thus
   - the requirements for the installation space of the actuator can be reduced
   - the weight of primary damped masses within the chassis can be reduced
   - the costs of the braking unit can be reduced
3. No conversion of the board system to 42V is needed
4. Increased dynamics, controllability and stability

THE NEXT GENERATION

Fig.9: Second Prototype

A follow-up prototype (fig.9) already includes fail-safe concepts, e.g. a second motor unit delivering half the work load under normal conditions but capable of emergency braking as well as solutions for an electric park brake using defined slack within the power train. Most important feature of the power train concept is the active compensation of said slack while operating within the zero-force-control-mode (optimal operating point).

CONCLUSION AND OUTLOOK

eBrake® - the new and unique "brake-by-wire" technology, developed at the German Aerospace Centre, DLR e.V. is described. It is based on an electric powered controlled friction brake with high self-reinforcement capability. By intelligently controlling a brake wedge, the kinetic energy (momentum) of a vehicle is smartly transformed into braking power.
A control technology is outlined which avoids the jamming of the brake. The mechanical model is described and the basic formula for the systems behavior is deduced. The progressions of the characteristic brake factors of two different eBrake®-solutions are discussed and further optimization potentials are shown.
A comparison with other braking systems, following the "conventional" braking philosophy, in particular brake-by-wire systems, is given and the following advantages of the eBrake® concept are pointed out:

- the average energy consumption of the actuator can significantly reduced
- the actuator can be enormously downsized (installation space, costs, weight)
- no conversion of the board system to 42V is needed
- system dynamics, controllability and stability are increased

Most notably increased dynamics will lead to improvements in reaction time, shortening of ABS-cycles and thus reduced braking distances. This is an important

contribution to increase active safety and reduce stress for the driver.
Further benefits of eBrake® are easy maintenance, simple diagnosis and service programs not to mention the ecological vantage of total lack of hydraulic fluids. Active air gap adjustment will come out in lower mileage, wear are tear and thus lower maintenance costs.
Apart from automobiles, the intelligent mechatronic eBrake® can be used for rail vehicles, mobile cranes as well as for applications within the fields of mechanical engineering and plant engineering. In these cases it is also possible to achieve serial production maturity within a relatively short time frame.
As all new developments, however, the intelligent mechatronic wedge brake will also need time to become recognized as a standard. What now still sounds like far-off future will soon become reality. In any case, there are many good reasons why we believe that in a few years, most drivers will be braking with a system, which our ancestors were already able to rely on totally.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

F_m: motor force
F_n: normal force
F_{aux}: auxiliary force
F_b: braking force
$F_{b,max}$: maximum braking force (nominal value)
R: reaction force
α: wedge angle
c: caliper stiffness
x: wedge position/ deflection

APPENDIX

eStop® und eBrake® are registered Trademarks of eStop® - innovative brake technology - GmbH