# Development and validation of Multi-Mode® EMB, a new electromagnetic brake for thin slab casters

*A new electromagnetic brake (EMB) for thin slab casters has been developed to go beyond the conventional braking function. Different magnetic configurations have been studied to understand steel flow responses to various magnetic configurations, resulting in a new concept with multiple poles and functions. It efficiently provides three functions: (i) braking a strong double-roll flow, (ii) damping the vertical meniscus fluctuations, and (iii) stabilising the right-left instabilities to stop bias flow. This new EMB has been validated on a 1:1 scale simulation plant for various SEN geometries, mould sections and casting speeds up to 10m/min, and is now commercialised under the name Multi-Mode® EMB.*

**Authors:** Siebo Kunstreich, Thierry Gautreau, Jean-Yves Ren, Andrea Codutti, Fabio Guastini and Marco Petronio
*Danieli Rotelec and Danieli Research Center*

In the 1980s, when steel was less clean than today, the liquid steel would enter the slab caster moulds with a certain kinetic energy and dive down below the mould carrying a large number of non-metallic inclusions. Because of the curvature of the machines, when these particles started to float out due to the buoyancy forces, they would be trapped in the strand solidification front on the loose side of the slabs. This was called the 'inside inclusion band' or 'quarter-thickness inclusion band' and, of course, was detrimental to the quality of the rolled strip.

To help reduce this problem, the electromagnetic brake was developed by Kawasaki and ASEA with the aim of reducing the velocity of the downward steel flow so that the inclusions would not dive so far and would float up to the meniscus without being trapped in the solidification front. This technology, known as EMBr, evolved from EMBr to EMBr-Ruler and to FC-Mould Generation 1, 2 and 3, but still focuses on the braking of the downward flow**[1]**.

This, we believe, is an obsolete concept – the downward steel flow and associated inclusions are no longer the main problem. This is not really thanks to the brakes, but mainly because of the vertical bending design of modern slab casters whose vertical length of 3-4m below the meniscus permits the floating out of most of the inclusions, and also because the liquid steel entering the mould is now much cleaner due to improved steel making and tundish practices.

We believe that the main slab quality problems today are surface and subsurface defects and the inclusions that are generated by the steel flow inside the mould, not below the mould. The credo to follow is: Control the steel flow in the mould and you control the slab quality**[2]**.

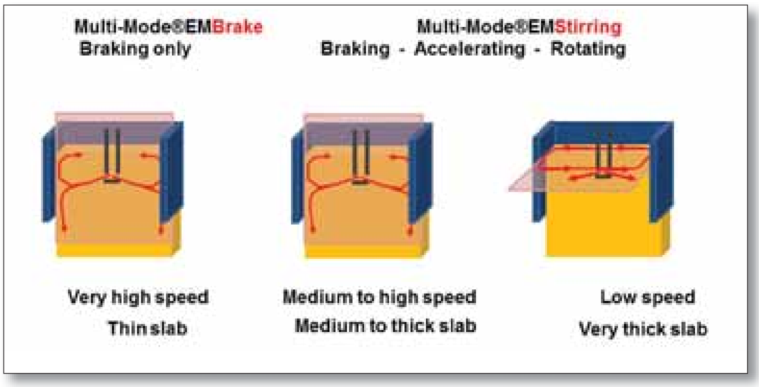


**Fig 1 Danieli Rotelec's concept of EM actuators for all slab casters**

For thick slab casters, we have developed Multi-Mode® EMS (MM-EMS), starting with NKK's braking and accelerating functions EMLS/EMLA, and added rotating functions, new operating modes and new control software**[3]**. MM-EMS permits us to control, quantitatively, the steel flow velocities by transforming unstable, single-roll and too-fast or too-slow double-roll flows into an optimised double-roll flow or to generate a rotational flow at the meniscus. MM-EMS uses linear stirrers (linear induction motors with travelling magnetic fields) that are powered by 2 or 3 phase AC currents (*see Figure 1*).

For thin slab casters, however, EMS is not compulsory:

- Rotational flow at the meniscus cannot be generated because of the flatness of the thin slab
- The accelerating function to transform single-roll flow into double-roll flow is not required because there is no

▷

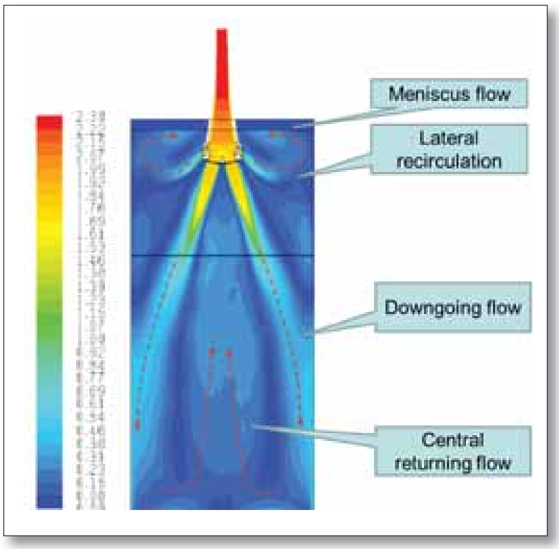


Fig 2 **Double-roll flow in thin slab caster with 4-port SEN**

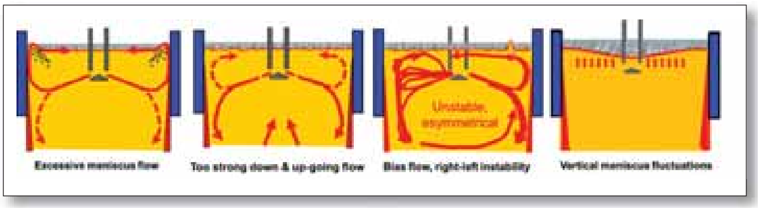


Fig 3 **Four flow pattern phenomena in the mould of thin slab casters that generate slab defects**

single-roll flow in thin slab moulds due to the absence of argon bubbling

- The acceleration function to increase the double-roll flow velocity is not required because modern thin slab casters operate at high casting speeds for productivity reasons and, hence, need only braking functions.

Therefore, for thin slab casters EMS can be replaced by EMB that uses the static magnetic field of an electromagnet powered by DC current, provided, however, an advanced braking system is developed that provides more functions for steel flow control inside the mould than the global braking of conventional EMBr or EMBr Ruler. This was the purpose of our development work and is reported here.

## WHICH STEEL FLOW PATTERN GENERATES WHICH DEFECTS?

Before describing the different functions of the new EMB, we show which steel flow pattern generates which type of surface and subsurface defects in thin slab casters.

The predominant steel flow pattern is a too-strong double-roll as shown in the CFD simulation in *Figure 2*.

Since argon bubbling is not used on thin slabs, we can disregard single-roll flow (unless SENs with meniscus ports generate a partial single roll flow) that exists in medium to thick slab moulds when the rising argon bubbles are the predominant flow driving force.

In moulds operating with two-port SENs (as in thick slab casters) there is only one common flow exiting the SEN on each side that divides into lateral recirculation flow going up to the meniscus and lateral flow going down when it hits the narrow mould faces. In moulds operating with four-port SENs, which is frequently the case in thin slab casters, the lateral recirculation flow and the downward flow are separated (*see Figure 2*).

The quality problems on thin slab casters that are generated by a too-fast double-roll flow pattern due to high casting speed/high throughput are the same, regardless of whether 2 or 4 port SENs are used (*see Figure 3*):

- The first and best-known problem is excessive meniscus flow velocity that is generated by too-fast double-roll flow. In this case, the steel flow generates standing waves and turbulence close to the narrow mould faces and an excessive horizontal meniscus flow velocity. The consequence is a thin powder layer close to the narrow faces and poor lubrication, uneven shell thickness and powder entrapment. These problems exist if the meniscus steel velocity exceeds 0.3m/sec.
- The second problem, connected to the first, is right-left flow instabilities that are generated by a too-strong central returning flow, itself generated by a too-fast downward portion of the double-roll flow.
- The third and worst problems are bias flow and asymmetrical flow with respect to the SEN axis, right-left instabilities, meniscus waves and turbulences. Unstable flow is the worst case for surface/subsurface quality.
- The fourth problem, again the consequence of a too-fast double-roll flow, is excessive vertical meniscus fluctuation/meniscus waviness. This generates local perturbation of mould powder lubrication, uneven shell formation, and longitudinal cracks.

These four problems are presented separately for didactical reasons only. In reality, they are not independent of each other – a typical problem in fluid mechanics – and which makes it particularly difficult to find a good solution to control them, as will be shown below.

## RESEARCH & DEVELOPMENT OF THE NEW CONCEPT

Our purpose was to develop a new system that can go beyond a global braking action, ie, that can specifically address the above four flow problems. It seemed obvious that a more sophisticated magnetic configuration than

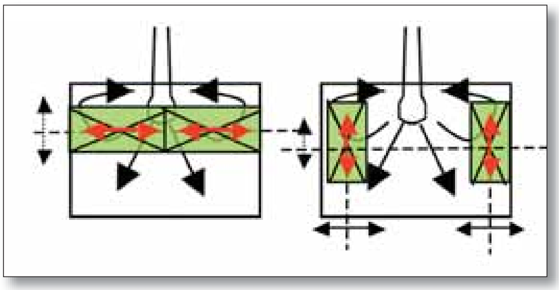


Fig 4a **Simulations with AC application (EMS)**

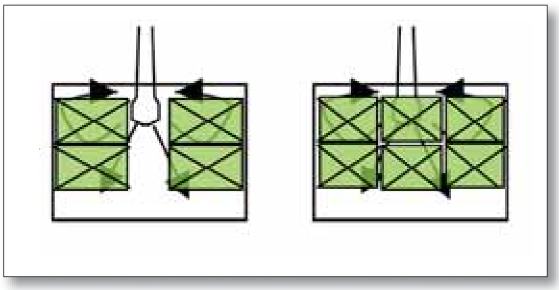


Fig 4b **Simulations with DC application (EMB)**

that of the conventional EMBr or EMBr Ruler would be necessary. A large variety of magnetic configurations with AC or DC fields has been investigated (*see Figure 4*) with coupled electromagnetic and CFD simulations using a free meniscus surface and reproducing the geometry of the SEN and the funnel mould with the purpose of identifying the position, area and strength of the magnetic fields that would be useful. To select the 'good' configurations, we compared vertical meniscus fluctuations, velocity of horizontal meniscus flow and of down-going flow obtained without and with magnetic fields.

**EMS stirring applications** 2 or 3 phase AC current with horizontal travelling fields at different positions, as well as vertical travelling fields close to the narrow mould faces, looked interesting because of their ability to add an accelerating function to the braking function when casting at slow speed/low throughput (*see Figure 4a*). They were abandoned not only because of high energy consumption due to the thick copper plates, but mainly because of the assumption that thin slab casters would operate in future at high casting speed/high throughput and, hence, would not need accelerating function like medium to thick slab casters.

**EMB braking applications** Single-phase DC current was simulated with different pole positions, sizes and different coil current combinations covering the major area of the mould (*see Figure 4b*).

We underline the fact that without simulations it is not possible to predict, and also difficult to understand, the relationship between magnetic field configuration and flow response, because the common belief that liquid steel flow can be stopped with EMB is wrong. Unlike the solid disc of the eddy current brake in trucks and buses, liquid flow is not 'well-behaved' through the obstacle of the magnetic field that generates the braking force: it more likely goes around. If the braking force is strong enough ie, magnetic field must be strong and steel velocity must be high (remember: the braking force is proportional to the steel velocity and to the square of the magnetic field), the EMB can act like a wall that deviates the flow direction, but neither the flow is stopped nor the direction is under control unless one uses different magnetic poles that can create a channelling effect for the flow.

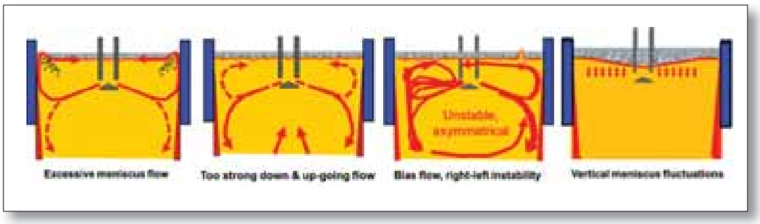


Fig 5 **New EMB multi-pole configurations developed to address the specific problems of *Figure 3***

The solution that was chosen is a multiple pole geometry that permits to address the specific flow problems with distinctive functions as indicated in *Figure 5*:

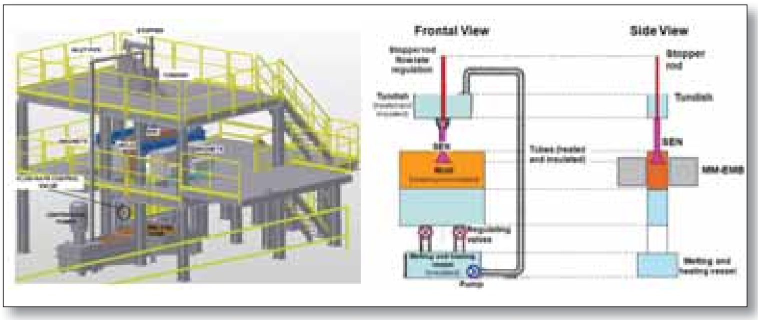
- Braking functions for the excessive horizontal meniscus flow and too-strong downward flow
- A stabilising function for the bias flow instabilities (and for a too-strong central returning flow)
- A damping function for the vertical meniscus fluctuations.

These different functions correspond to different magnetic configurations that can be activated in different combinations by appropriate current settings of different power supplies, ie, in different operating modes. Because of the different operating modes and in analogy to our technology for thick slab casters, we have named this new EMB Multi-Mode® Electro-Magnetic Brake (MM-EMB).

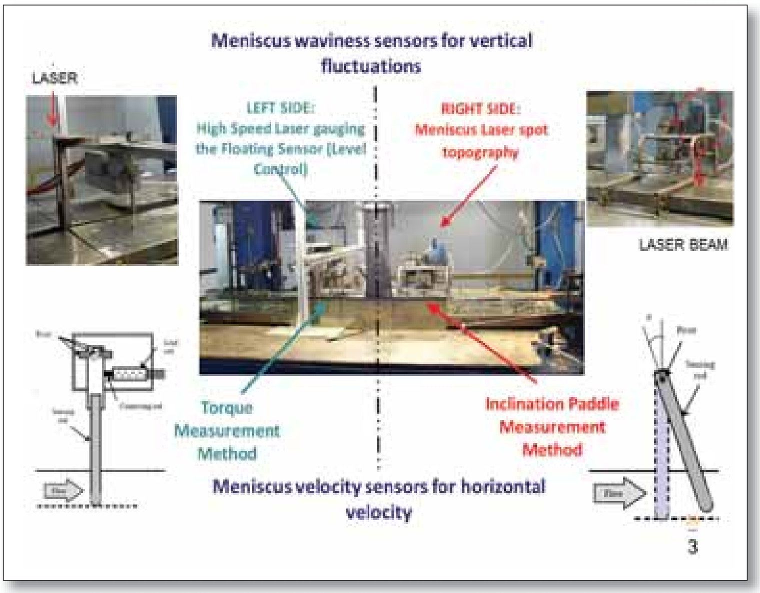
## VALIDATION OF MM-EMB

Based on the above theoretical work and considering the very complex concept, we felt it necessary to validate it by experimental work. We therefore designed and built an EMB prototype at Danieli Rotelec in France and a 1:1 scale simulation and demonstration plant at the Danieli R&D Center in Italy that we believe is unique in the world (*see Figure 6*).

Using a recirculation loop of low melting point (138°C) bismuth-tin alloy, we reproduce the steel flow conditions ▷



Ⓐ Fig 6 **Simulation and demonstration plant in Danieli R&D Center, Italy to validate the new EMB concept**



Ⓐ Fig 7 **Experimental set-up to measure the meniscus flow velocity and meniscus waviness on both sides of the SEN**

in a plant with a full scale SEN and funnel mould. The Bi-Sn alloy was chosen because its physical properties – its electrical conductivity, density and viscosity are very close to those of liquid steel. Therefore we can trust that the flow in the mould and the reaction under the electromagnetic forces will be very similar to the steel flow in a caster mould.

On the top of this facility is a small tundish with an industrial stopper that provides the liquid metal to the SEN and to the mould. Below the mould, the liquid metal is recovered by a specially designed collector that prevents turbulence transmission upwards; the casting speed is simulated by a flow control valve at the output of the collector. The liquid metal then flows into a tank from which it is recirculated by a pump to the tundish. The EMB is installed on both sides of the mould.

Casting speeds from 4.2 to 11.7m/min were simulated; mould sections were used for 102.5mm thickness, widths of 1,800, 1,530, 1,250 and 990mm, and different SEN geometries were tested.

The mould is equipped with four sensors (*see Figure 7*), two on each side of the SEN. Two sensing rods immersed in the meniscus are used to measure horizontal meniscus velocity. Vertical meniscus fluctuations are measured by recording the up and down movement of a swimmer on the left side of the SEN, and meniscus topography is measured by a laser scanner on the right side of the SEN. With this instrumentation, we can measure the liquid metal flow on the left and right side of the SEN and compare the flow under condition with EMB switched On or Off. The test parameters are mould width, throughput (ie, casting speed) and electrical current settings of the electromagnets.

*Figure 8* shows the meniscus shape with MM-EMB switched OFF and ON. The example is for a four-port SEN, mould size 1,800 x 100mm, casting speed 6.9m/min (throughput 1,100 l/min).

*Figure 9a* shows the horizontal meniscus flow velocity on the left and right side of the SEN versus time for a mould section of 1,180mm and casting speed of 7.9m/min.: With EMB switched OFF, meniscus velocity is biased at 0.5 and 0.3m/sec at left and right side of SEN, respectively. With EMB switched ON the bias flow is stabilised and the meniscus velocity is braked down to 0.12m/sec.

*Figure 9b* shows the vertical meniscus fluctuations in terms of standard deviation (sigma) of the fluctuations versus time. With brake switched OFF, the standard deviation of the vertical fluctuations is 1.3mm (corresponding to 95% of fluctuation ≤ 2.6mm), with brake switched ON, the damping function has reduced the fluctuations from sigma 1.3mm to 0.7mm (corresponding to 95% of fluctuations ≤ ±1.4mm).

The example of *Figure 9a* refers to a magnetic field configuration that enhances the braking function against the damping function. *Figure 9b* shows, for the same case, a different magnetic field configuration that is set to enhance the damping function against the braking function. The figure shows again that with EMB switched OFF, the meniscus velocity is biased at 0.5 and 0.3m/sec at left and right side of the SEN, respectively. With EMB switched ON the bias flow is stabilised and the meniscus velocity is braked down to 0.19m/sec. *Figure 9b* shows the vertical meniscus fluctuations in terms of standard deviation of the fluctuations, versus time with brake switched OFF and ON. The damping function has reduced the fluctuations from sigma 1.8 mm to 0.35mm.

Comparing *Figures 9a and 9b* illustrates two different operating modes with different magnetic field configurations: *Figure 9a* with enforced braking, shows braking down by ≈70% and damping down by ≈45%, whereas *Figure 9b* with enforced damping, shows braking down by ≈50% and damping down by ≈80%. The stabilising function is activated in both cases.

These two examples illustrate the outstanding ability of the new EMB to simultaneously stabilise the right-left asymmetry (equalises the bias flow), brake the horizontal meniscus flow velocity and dampen the vertical meniscus fluctuations. Moreover, they show that MM-EMB is a flexible tool, because the braking and damping functions can be modulated according to casting conditions or steel grade/defect type. This can be used in the following way: The braking function can be increased over the damping function if the main problem is excessive meniscus velocity, i.e. powder based inclusions, whereas the braking function can be decreased over the damping function if the main problem is excessive meniscus fluctuation and/or cold meniscus, ie, bad lubrication, insufficient powder melting, stickers, alumina based inclusions.

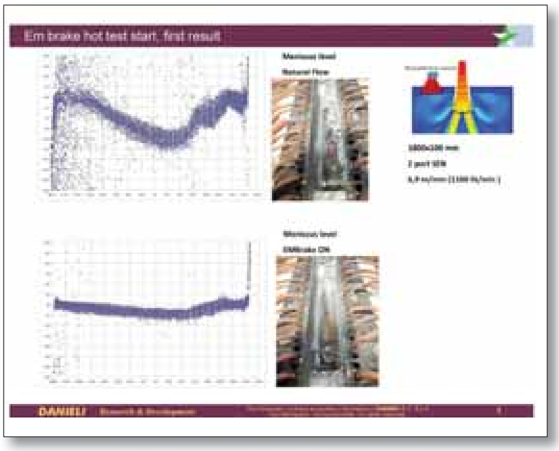
## INSTALLATION OF MM-EMB ON A CASTER

In this last section we will show how MM-EMS can be installed on a thin slab caster, the equipment required for a complete MM-EMB installation, and the mechanical interface between EMB and caster.

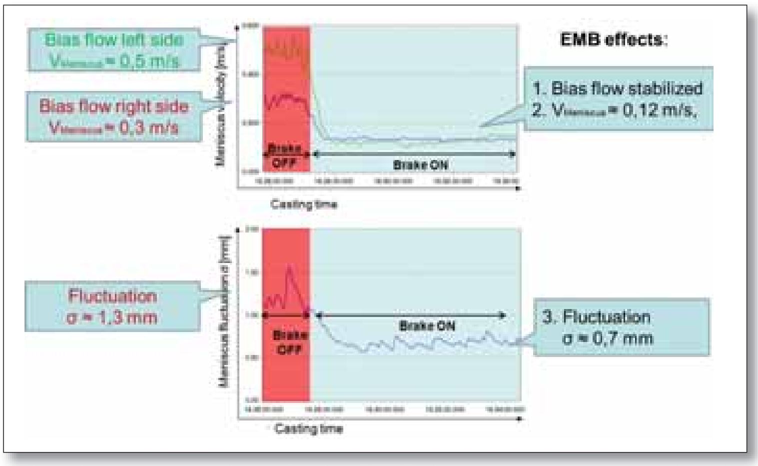
*Figure 10* shows a block diagram of the MM-EMB equipment for one strand of a thin slab caster. Two EMB units are installed in a cavity behind the backup plates of the broad mould faces, one on each side. Special heat-resistant power cables go from there to a connection box outside the cooling chamber, then from this box standard power cables go to the power supplies (AC/DC converters) in the electrical room. The power supplies are connected through power transformers to the low-voltage or medium-voltage network. The number of power supplies can range from 3 to 5 according to the desired degree of sophistication of the automatic process control. Operation with only one power supply is possible, but this implies only one operating mode.

Demineralised cooling water from a closed loop pure water unit and dry air or nitrogen are also connected to the rear of the brake units by flexible hoses. A PLC installed in the electrical room controls the full equipment. It is connected to the automatic controller (PC) with maintenance HMI that provides the different coil current setting values to the PLC and that is connected by industrial Ethernet bus to the level 2 or PLC of the caster. It provides full automatic operation of the system through a dedicated software using a set-up message as input data from level 2, ie, heat number, steel grade, operating mode (plus SEN geometry and casting powder if different types are used), and real time data that can vary during casting, ie, casting speed and slab width. The job of the operator is limited to the selection of the operating mode or of the steel grade and powder specification (the operating mode can be pre-programmed as function of steel grade and powder), however manual operation is possible any time on the HMI in the operator room.

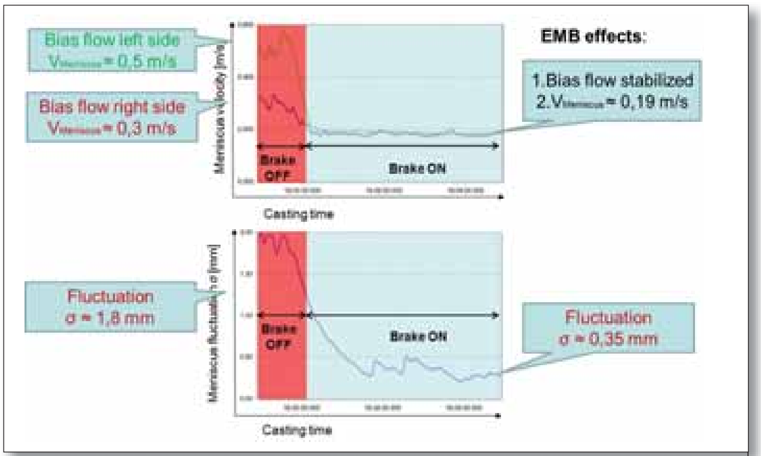
▷



Ⓐ Fig 8 **Measured meniscus profile without EMB (*top*) and with EMB (*bottom*)**



Ⓐ Fig 9a **Horizontal meniscus flow velocity (*top*) and vertical meniscus fluctuations (*bottom*) measured without and with EMB in an operating mode set to enhance the braking function**



Ⓐ Fig 9b **Same case as *Figure 9a,* but with EMB in an operating mode set to enhance the damping function**

▷

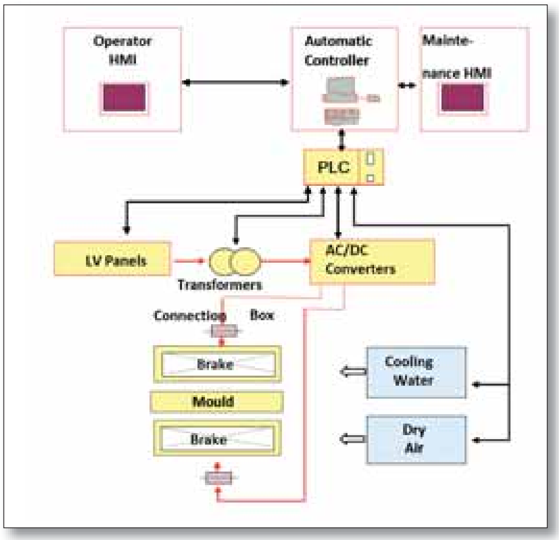


**Fig 10 Block diagram of MM-EMB for one strand**

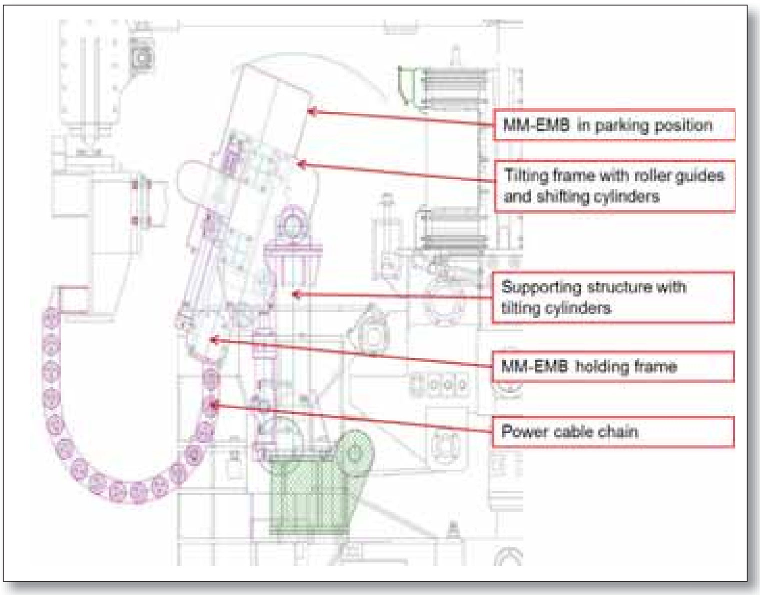


**Fig 11 Typical installation of MM-EMB on a manipulator**

*Figure 11* shows a typical installation of the MM-EMB on a manipulator that withdraws the brake from the mould and tilts it into a parking position during mould change or caster maintenance. The mould itself must be designed with a cavity between the water boxes to insert the EMB unit as close as possible behind the mould back-up plates. The manipulator keeps the brake in a fixed position, ie, the brake does not oscillate, and hence does not add any additional weight to the mould nor to the oscillation mechanism. All connections for electrical power cables, cooling water and dry air are located on a cable chain that remains connected to the back side of the brake.

## CONCLUSIONS

A new concept of electromagnetic brake for thin slab casters has been developed and tested on a simulation plant at scale 1:1. Its three functions braking, stabilising and damping have been validated. Within the large range of sections, casting speeds and SEN geometries that have been tested, it has always been able to brake the horizontal meniscus flow velocities down to below 0.3m/s, to dampen the vertical meniscus fluctuations to below 0.8mm (sigma) and to compensate the left/right bias flow. The new EMB is a flexible tool because it permits enhancement of either the braking or the damping function by means of different operating modes. It is commercialised under the name of Multi-Mode® EMB.

## ACKNOWLEDGEMENTS

The authors acknowledge with thanks the support of Danieli Research Center, Danieli Davy Distington and Danieli Automation who have financed this work. **MS**

*Siebo Kunstreich is President of Danieli Rotelec, Thierry Gautreau, Jean-Yves Ren are with Danieli Rotelec, Paris, France. Andrea Codutti, Fabio Guastini, and Marco Petronio are with Danieli Research Center, Buttrio, Italy.*

**CONTACT:** siebo.kunstreich@danieli-rotelec.fr

## REFERENCES

**[1]** H Yang, M Sedén, N Jacobson, J-E Eriksson and H Hackl, 'Development of the Third-Generation FC Mold by Numerical and Water Model Simulations', in *AISTech Conference Proceedings*, PR-362-130-2012

**[2]** P H Dauby, 'Real Flows in Continuous Casting Molds', in *AIST Transactions*, 8, 6, pp152-160, 2011

**[3]** S Kunstreich, P H Dauby, S-K Baek and S-M.Lee, 'Multi-Mode EMS in Thick Slab Caster Molds and Effect on Coil Quality and Machine Performance', in *Proceedings 5th European Continuous Casting Conferences*, Nice, France, 2, p482, 2005.

▷