Modelling and controlling the road finishing process

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ABSTRACT

Among the road construction tasks, finishing is one of the most important because, once carried out, nothing can be done anymore to improve the quality of the profile.

The behaviour of this equipment and of the material it handles is more complicated that it seems to be.

The most significant point of this paper is the original mathematical model of the process that is presented in the first part.

Then, the authors show how this model accounts for the main behaviours of the process, already known or just detected, and quote some applications of it.

Among these, there is the possibility of using the model for elaboration of high performance control systems of the finishing equipment.

In the last part of the paper, the authors describe more particularly two types of control systems; one precise levelling control using an absolute reference like a guide wire or a laser plane and one for improving the most common working mode of the equipment (without absolute reference) using an original measurement of the average thickness of the layer.

I - INTRODUCTION - THE FINISHER

1.1 - ITS ROLE

The finisher is the machine that spreads the last layers on most types of roads, except on concrete roads.

Its role is therefore essential as, after its passage, no profile correction can be done as the rollers can but only impair the levelling characteristics.

This machine was invented by the US BARBER GREENE company (around years 1930) which has also developed a rough mathematical model, which has been accepted until now by most professional bodies of the trade [BAR-72].

Its three main applications on the material (asphalt or bituminous concrete) are as follows :

- spreading (supply and crosswise distribution)
- calibration (obtention of the desired width and thickness)
- pre-compaction (first densification of the layer)

1.2 - BRIEF DESCRIPTION - MACHINE BEHAVIOUR

The finisher essentially consists of a tractor (most of the time equipped with a hydraulic power pack) and a so-called "floating screed" linked to the tractor by means of two side arms hinged to the tow points. These tow points can be moved by means of two hydraulic cylinders mounted on tractor's chassis.

The "arm + screed" assembly can be diagrammatically represented as a segment connecting the rear end of the screed A (trailing edge) to the tow point B, as shown on figure 1.

The position of A depends on the profile of the support, and on a relatively complicated balance of the forces between the equipment and the material.

The position of B depends on the profile of the support, geometry of the tractor, and control (voluntary action on the height of the tow points).

The line AB may rotate either around A when B is moving, or around B when A is moving.

The control problem is to adjust B so that A is at the desired setting value.

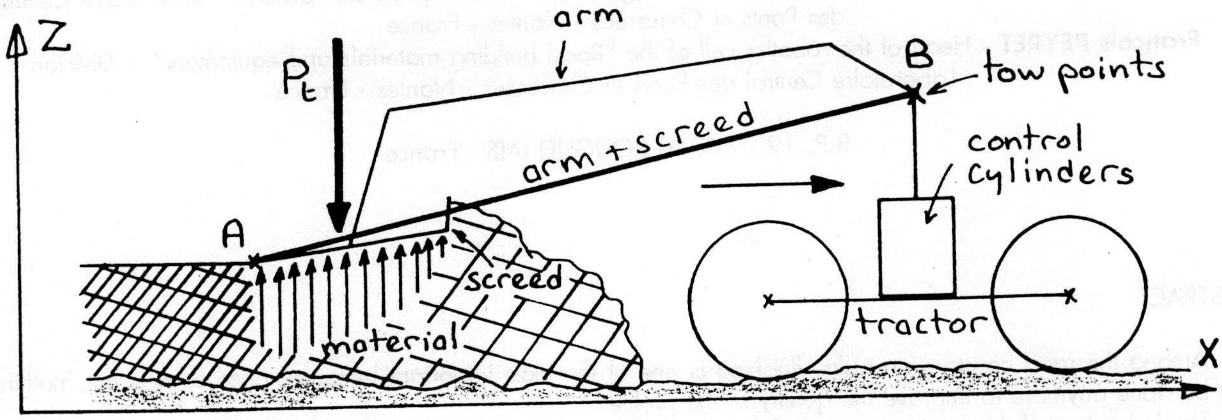


Fig 1 - Geometrical schematic representation of the arm + screed assembly

1.3 - FINISHER OPERATING MODES

The finisher has two essential operating modes :

- Manual mode : the machine is adjusted so that its balance will correspond to the desired position of A and, from time to time, when a certain drift occurs, balance is restored by manual adjustment of B.

- Guided mode : a mechanical feeler is installed on the arm, and an automatic system will adjust B so that the feeler will most accurately follow an external reference. This reference may be a guidewire, the lower course, the adjacent course assumed as good, or the lower course levelled by means of a large beam supported in multiple points (BLAW-KNOW beam for example).

1.4 - HOW MACHINE OPERATION CAN BE IMPROVED

Manual mode (open loop)

This mode is often used on work sites when it is desired to spread a layer of constant average thickness on a support assumed to be at the correct profile.

The thickness is roughly checked visually, or with a ruler, and manual adjustments are detrimental to the quality.

An automatic control system, starting from a fair evaluation of the average thickness, would constitute a considerable improvement.

Guided mode (closed loop)

This mode could be improved in multiple ways :

-Improvement of sensor and actuator quality and accuracy (clearances, linearity, leaks etc...)

-replacement of the heavy, dangerous and difficult to install material references by immaterial references (beacons) and contactless sensors (refer to J.F. LE CORRE communication).

-improvement of the correction functions by the introduction of high performance correctors calculated in terms of equipment behaviour and type of work to be carried out.

II - MODELISATION OF THE SPREADING PROCESS

2.1 - PHYSICAL MODEL

The basic assumptions are taken from a paper by Tom Shelley published in 1980 [SHE-80].

- No horizontal movement of the material under the screed (preservation of the mass in any vertical-elementary section)

- one to one relationship between compactness C of the material and the applied pressure P, having the following form :

[1] $C = A / (B\text{-}\mathrm{Log}\ P)$

On this basis, we have elaborated a two-dimension mathematical model and, subsequently, a digital model written in the Fortan language enabling the following to be calculated :

- Value and average compactness of the spread-out layer : Zr and Cr in terms of :
- . arm length and screed length : Lb and Lp
- . parameters A and B such as given in formula [1]
- . initial compactness of the material arriving under the screed : Ce
- . weight of the screed : Pt
- . profile of the support : Zs
- . position of the tow points : Zb

The simulations performed from this model have evidenced the following essential results [GOU-89] :

- After stabilization, the Zr/ Zb ratio varies between 0.5 and 0.8 for the main types of equipment units and materials.
- The relative variation of material thickness (referred to as r - Pre-compaction report) resulting from the passage of the levelling screed is fairly constant for a given assembly (material, equipment, setting values)

These results have been confirmed by full scale tests conducted on our experimental spreading test track in NANTES, as well as by many assessments on work sites.

2.2 - *THE KINEMATIC MODEL : EQUATIONS*

The last point related to the r constant has been taken as basis for the development of a simplified model, only handling geometrical magnitudes, and called kinematic model.

The notations are those given on figure 2 :

V : finisher progress speed Lb : length of the arm Lt : length of the screed r : pre-compaction ratio	) Constants
Zb (t) : elevation of tow point at time (t) Zs (t) : profile of the support at tow point level Zd (t) : elevation of screed cutting edge Zr (t) : elevation of screed trailing edge U(t) : control (cylinder outlet)	) variables

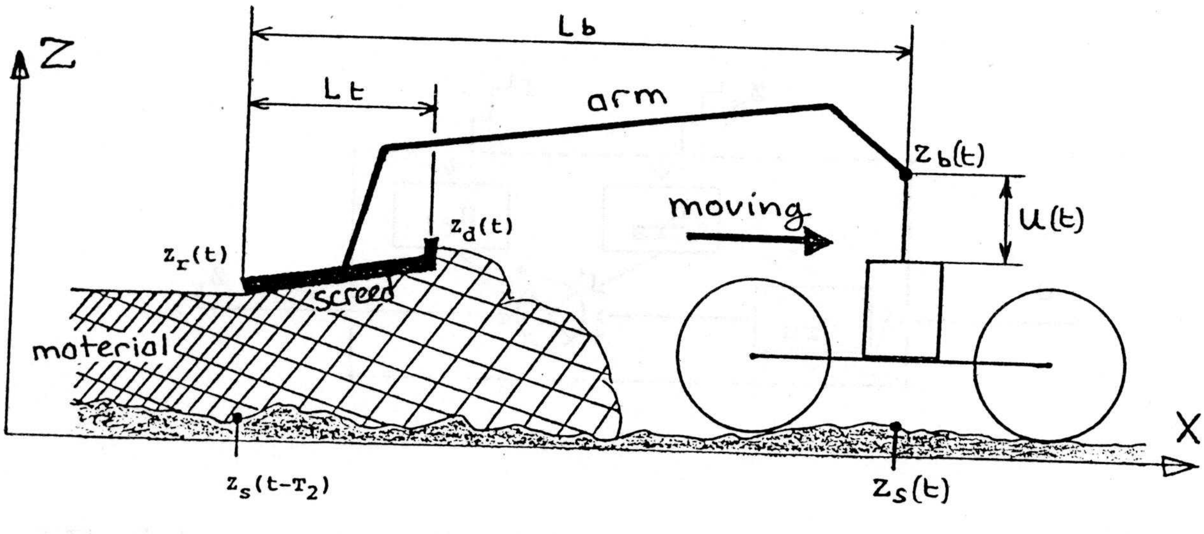


Figure 2 - parameters of the kinematic model

Simplification hypothesis :
- Influence of tractor's chassis : negligible :
  [2] $Zb(t) = Zs(t) + U(t) + K1$ ($K1$ = constant)
- "Arm + Screed" assembly not affected by any deformation :
  [3] $Zd(t) = aZb(t) + bZr(t) + K2$ ($K2$ = constant)

Note : $a = Lt / Lb$ and $b = 1 - a$

- Selecting the variables in such a way that $K1 = 0$ and $K2 = 0$, the first two equations of the model are obtained :

[4] $Zb(t) = Zs(t) + U(t)$
[5] $Zd(t) = a\ Zb(t) + b\ Zr(t)$

The third equation represents the heart of the model. It reflects the consistency of the pre-compaction ratio r :

$$\boxed{[6]\quad Zr(t) - Zs(t-T2) = r\ [Zd(t-T1) - Zs(t-T2)] + I(t)}$$

Note : $T2 = Lb/V$ and $T1 = Lt/V$

We have introduced in it the new variable I(t), representing the possible variations of the parameters assumed as constant (speed, characteristics of the material, adjustment of the finisher ...) and noted "pre-compaction instability".

Equations [4] [5] [6] modelize the kinematic behaviour of finisher arm + screed assembly, reduced at two dimensions.

2.3 - *THE KINEMATIC MODEL : TRANSFER FUNCTIONS*

Taking the LAPLACE transformed form of the variables, and designating the LAPLACE variable as "p", the following is obtained :

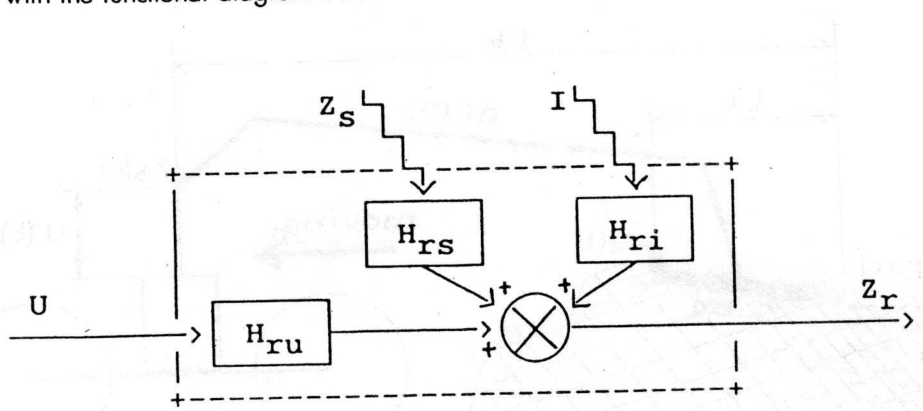
[7] $Zb(p) = Zs(p) + U(p)$
[8] $Zd(p) = aZb(p) + bZr(p)$
[9] $Zr(p) - \exp(-T2p)\ Zs(p) = r\ [\exp(-T1p)\ Zd(p) - \exp(-T2p)\ Zs(p)] + I(p)$

It results from the above three equations :

$$\boxed{[10]\quad Zr(p) = Hru(p)\ .\ U(p) + Hrs(p)\ .\ Zs(p) + Hri(p)\ .\ I(p)}$$

Hru(p), Hrs(p), Hri(p) functions of : a, b, r, T1, T2 representing the respective transfer functions between :
- the three input variables : U (control), Zs and I (disturbances)
- the single output : Zr

in accordance with the functional diagram below :



In order to represent the preceding transfer functions under linear form, we have approached exp(-Tp) as (1-1/2 Tp) / (1 + 1/2 Tp).

This approximation is valid in the low frequency range, which is the range of interest in our application. Approached transfer functions are thus obtained, which are presented under a "conventional" form :

$$H(p) = \frac{\sum_m bm\ p^m}{\sum_n an\ p^n}$$

for Hru : m = n = 1
for Hrs : m = n = 2
for Hri : m = n = 1

III - FINISHER SIMULATION IN OPEN LOOP

3.1 - *RESPONSES TO A STEP*

These responses allow the advantages of this model to be highlighted as compared to the former models of the BARBER GREENE type. The former models confounded the U input and the Zs input, only considering the single input variable Zb. Besides, they did not take into account the length of the screed (Lt), which is accounted for in our equation [6].

In reality the responses Zr/U = Hru and Zr/Zs = Hrs are different :

- The responses given by the model can be seen on figure 3. It shall be noted that the static gain (Hru modulus under stabilized rating) is different from 1 (comprised between 0.5 and 0.8 for usual cases). This gain is called "control efficiency".

- On the contrary, the static gain of Hrs is equal to 1 (BARBER GREENE model) but the response time is shorter than that announced by BARBER and is about twice as big as that of Hru

3.2 - *FREQUENTIAL RESPONSES*

That of Zr/Zs is interesting (refer to figure 4). It shall be noted that the gain corresponding to high frequencies does not tend toward zero but toward a value comprised between 0.1 and 0.2. This would evidence that short wavelengths defects are not as efficiently filtered as anticipated by the former models.

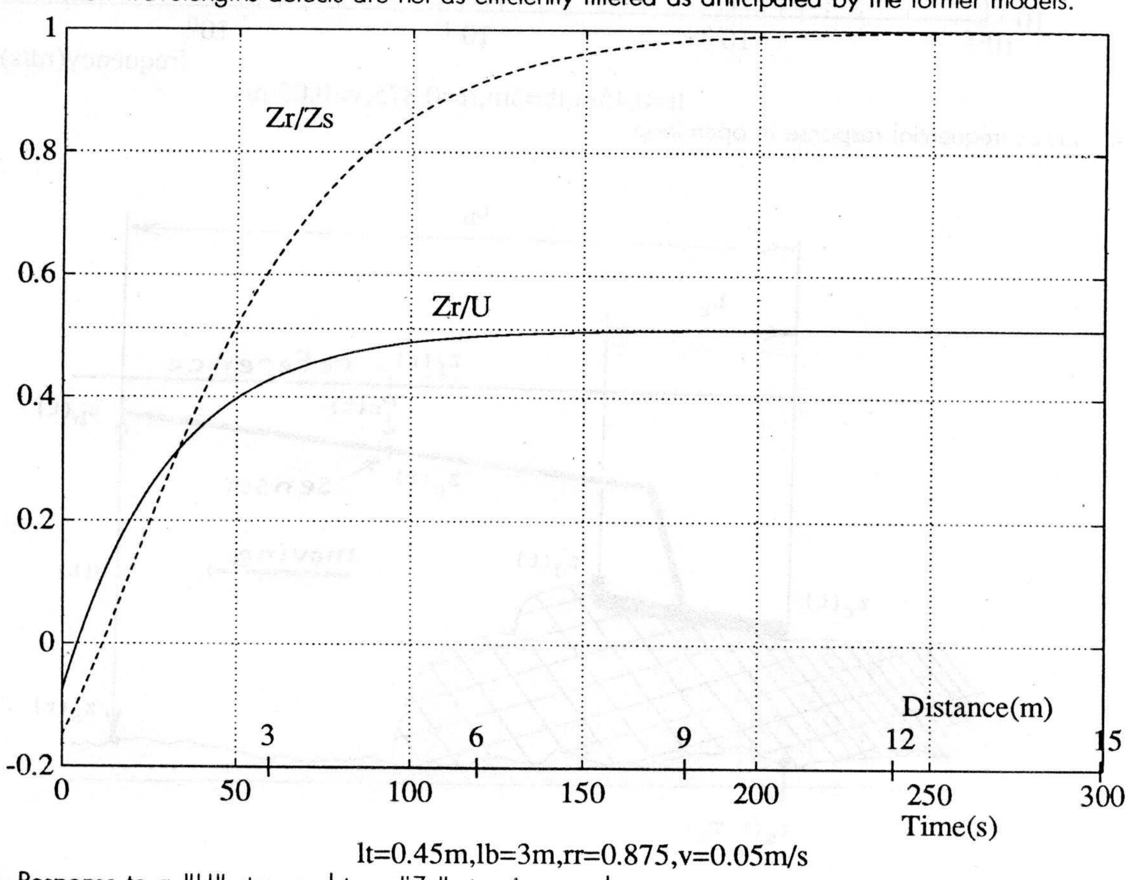


Figure 3 - Response to a "U" step and to a "Zs" step in open loop

IV - FINISHER STUDY IN CLOSED LOOP

4.1 - CONTROL IN TERMS OF ABSOLUTE LEVEL

The principle is shown on figure 5. The purpose of this control mode is to correct, as desired, the profile of the support deemed as defective essentially over long wavelengths, or showing significant deformations.

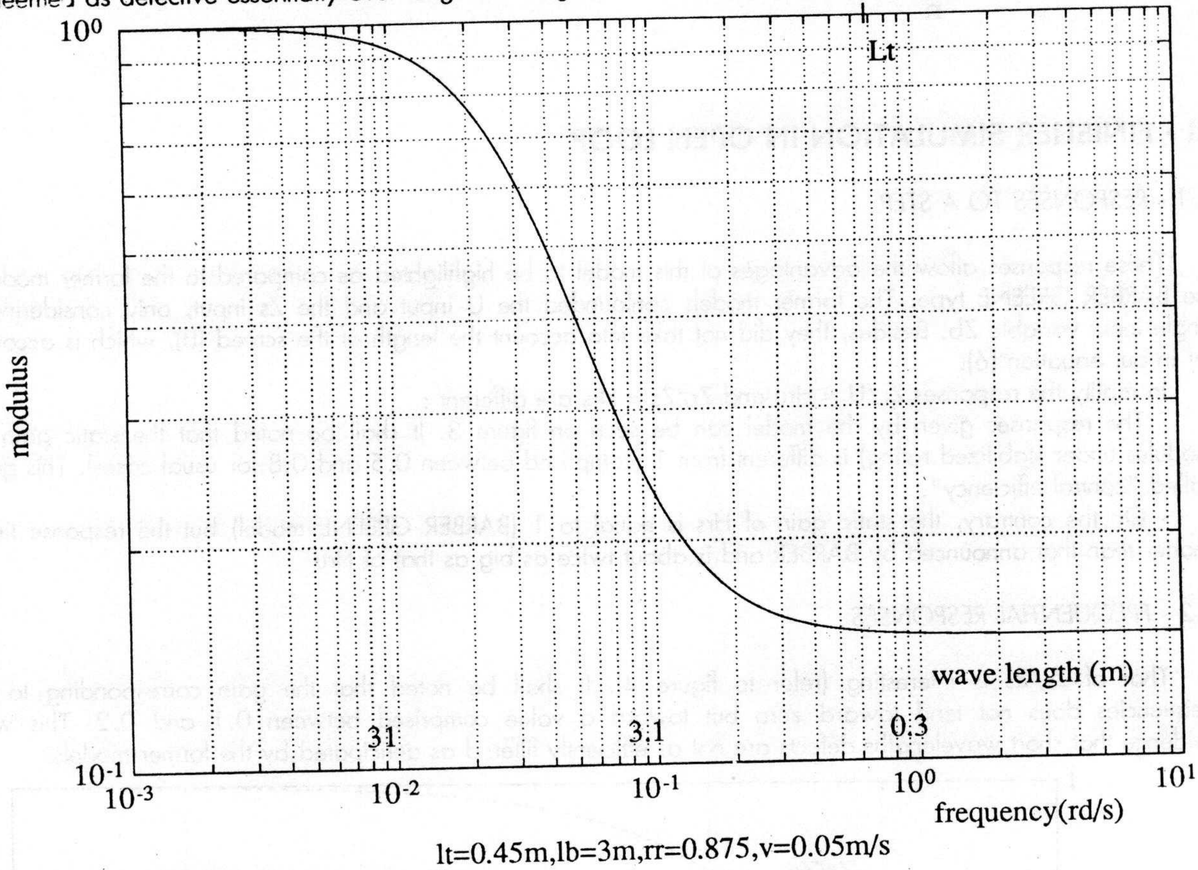


Figure 4 - Zr/Zs frequential response in open loop

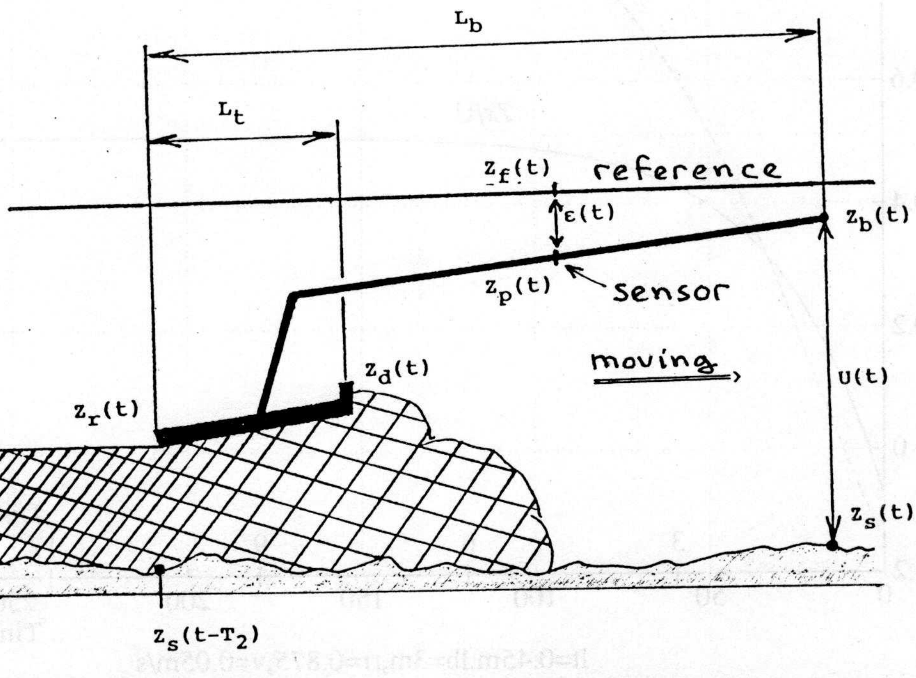


Figure 5 - Guiding in terms of absolute level

The functional diagram of the looped system is shown on figure 6.

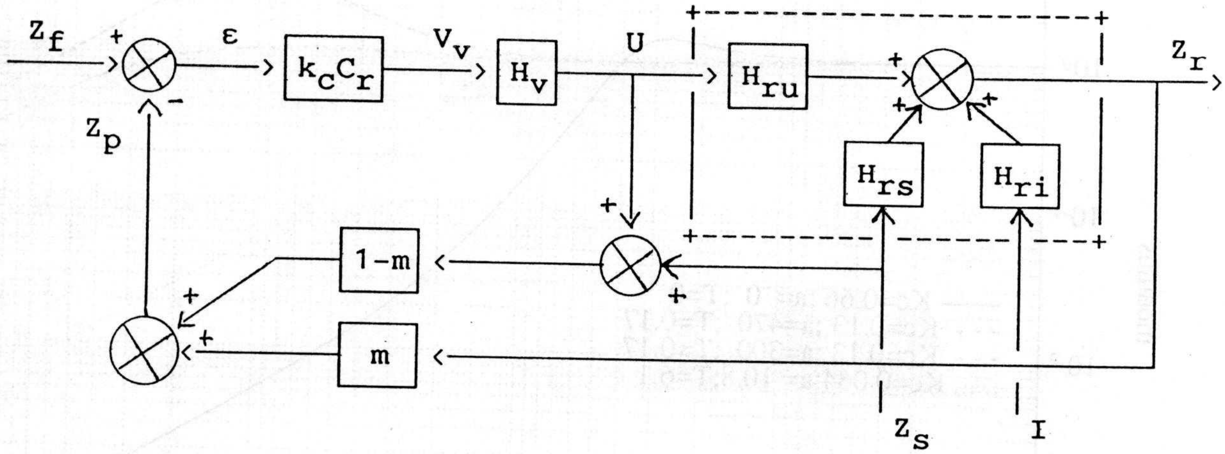


Figure 6 - Functional diagram of the level guided finisher

The position of the sensor is given by the following formula :

[11] Zp = mZr + (1-m) Zb

m = 1 sensor at trailing edge

m = 0 sensor at tow point

- Cr represents the transfer function of the corrector
- Hv represents the transfer function of the cylinder (Hv(p) = 1/p)
- Kc represents the static gain of the "corrector+cylinder" assembly

The following final expression is obtained :

[12] Zr = Frf . Zf + Frs . Zs + Fri. I

with Frf(p), Frs(p), Fri(p) functions of : Hru, Hrs, Hri, m, kc, Cr, Hv.

Sensor position

The analysis shows that the only possibility of obtaining a static gain = 1 for Frf - that is, to closely follow the reference - is to take m = 1, which means that the sensor has to be fixed at screed trailing edge.

This result is opposite to usual on-site practices, which require that the sensor be installed with m = 0.7 or so.

This difference is explained by an insufficient quality level of the elements (sensors, actuators) and correction function.

Calculating a corrector

Starting from the hypothesis with m = 1, we have calculated a corrector Cr and a gain kc, so that the looped system should follow the reference Zf as rapidly as practically possible, and without any oscillations.

Utilizing the BLACK locus graphical method [GIL-87], we have obtained :

kc = 0.13

Cr(p) = (1 + aTp) / (1+Tp) (phase lead corrector)

with a = 300 and T = 0.17s

The frequential response of Zr/Zf is given on figure 7 for four types of correctors.

The dynamic input of the phase lead corrector is clearly shown, as compared to pure gain (usual work corrector).

Sensitivity to Zs and I disturbances

As shown on Figure 8, the finisher looped through this corrector is much lesser affected by the defects of the support than the open loop finisher in the lower frequency ranges (w < 0.1 rad/s), but is slightly penalized in the higher frequencies.

It is all the same for the response curve of Zr/I

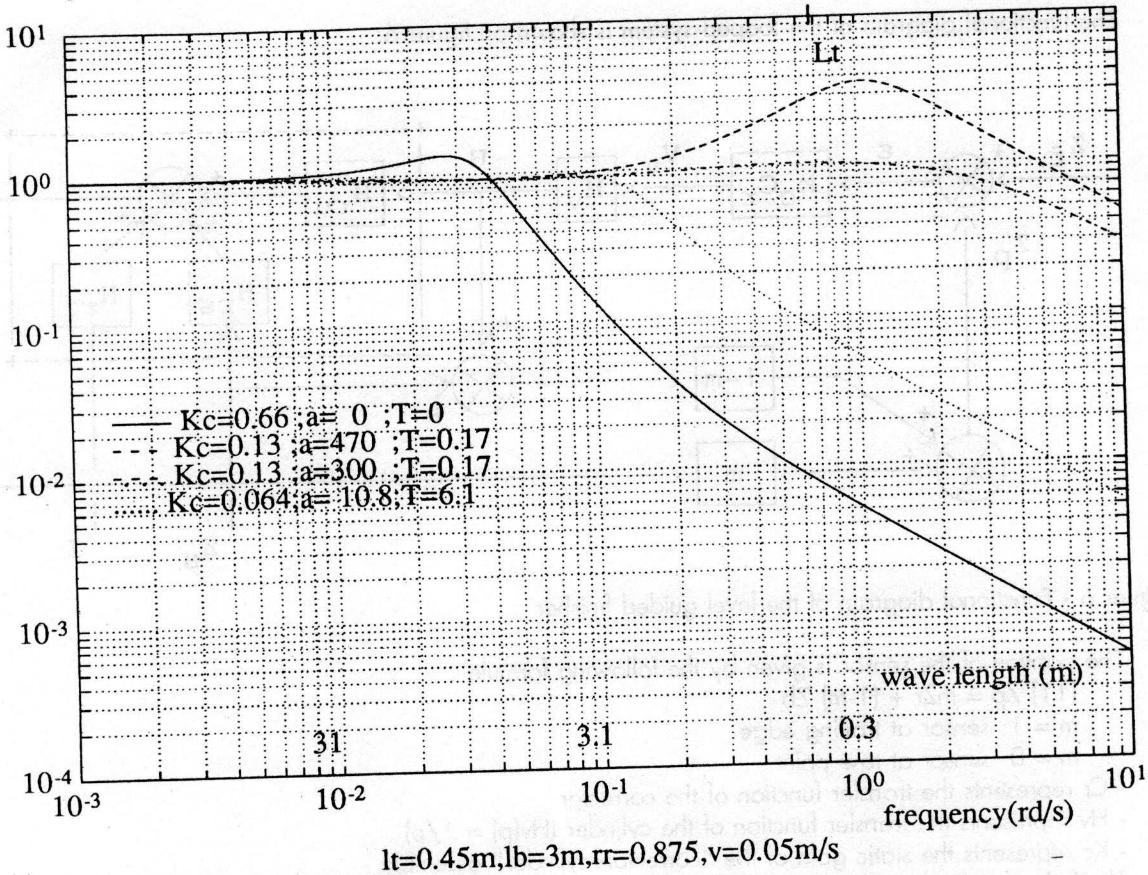


Figure 7 - Frequential response of Zr/Zt with correctors

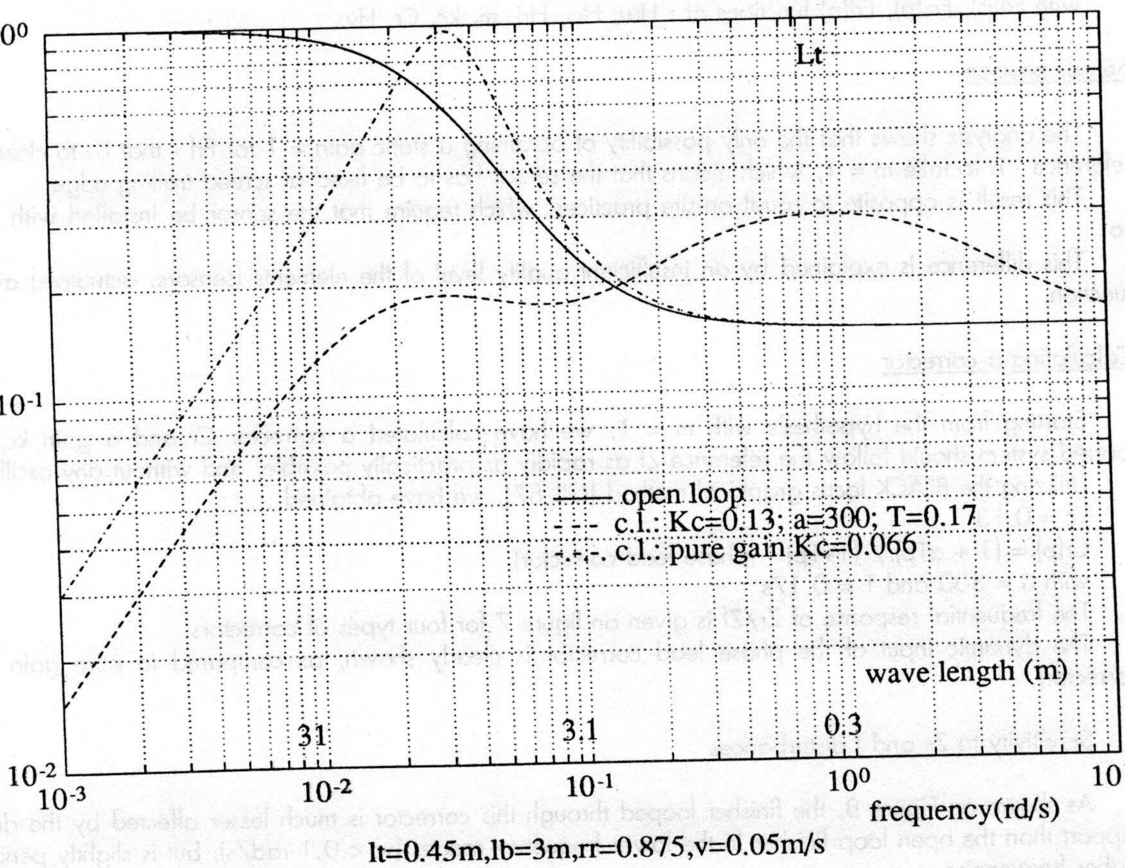


Figure 8 - Frequencial response of Zr/Zs : correctors compared to open loop

Simulations

On a sinusoidal support with 15 m wavelength, the looped finisher reduces the defect by 83% in a single run, whereas the open loop finisher will only achieve 18% reduction.

4.2 - CONTROL IN TERMS OF AVERAGE THICKNESS

In cases where the profile of the support is deemed as satisfactory in the higher wavelengths, no guiding system is used but confidence is placed in the natural self-levelling function of the equipment to spread a constant average thickness by smoothing the short wavelength defects.

However, if the finisher becomes out of adjustment, or if the characteristics of the material are changed (temperature for example), disturbance of the I(t) type will be undergone, and the quality of the spread profile can be seriously impaired before the human regulator reacts.

We have therefore imagined an original means of correction aimed at replacing, in full reliability, the open loop working mode consisting in spreading as constant thickness as practically possible.

The principle consists in :

- measuring the height of two points of the arm relative to the support
- calculating, by geometrical extrapolation, the evaluated thickness at the output (exact when the support is plane)
- averaging this evaluation over a certain distance in order to filter the profile variations of the support
- utilizing this averaged estimated thickness as feedback variable for closed loop regulation of the finisher with a constant pre-established thickness value.

At this stage, we shall not detail the equations used for this function. The approach is quite similar to that used in the calculations of paragraph 4.1.

The essential results are as follows :

- the more distant the sensors, the better the evaluation of the thickness
- averaging over a distance of 10 m at 5 cm measuring pitch appears to be quite sufficient
- the corrector used can be a simple pure gain
- in such conditions, the frequential response of Er/Zs is very close to that of the open loop finisher (refer to figure 9).
- on the contrary, the frequential responses of Er/I (refer to figure 10) show that, in the mode guided in terms of the average thickness, much lesser out of adjustment disturbances are encountered than in the open loop mode, which is in fact the objective to be attained.

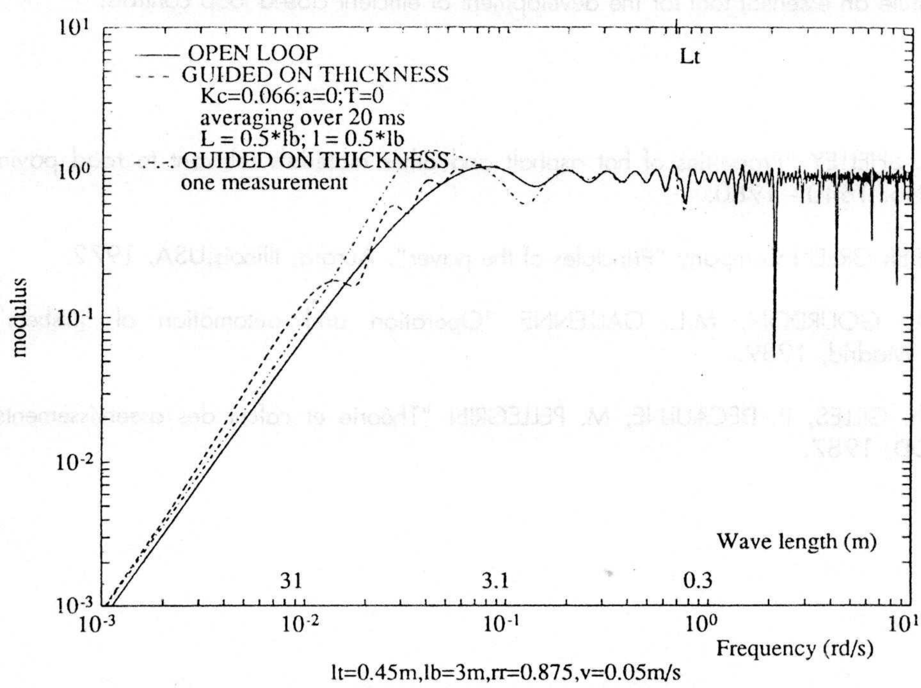


Figure 9 Er/Ez in average thickness guided mode

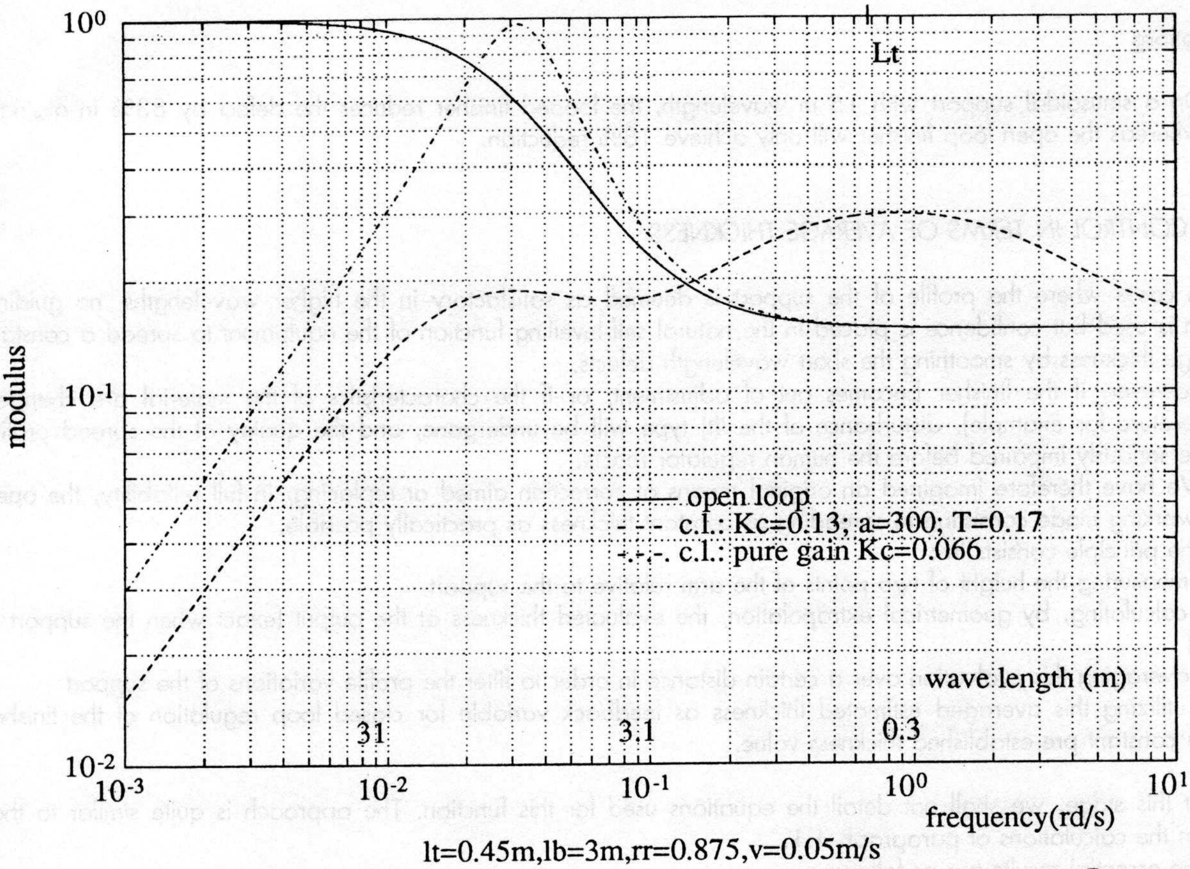


Figure 10 - Er/I in average thickness guided mode

V - CONCLUSIONS

We have shown how a kinematic model of the finisher, obtained from physical equations, and simplified by only keeping the geometrical variables, can highlight the knowledge of the process in a different manner, and can also constitute an essential tool for the development of efficient closed loop controls.

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