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COMPUTER CONTROL SYSTEM FOR HEAVY MACHINE FIXTURES MOTION AND ITS APPLICATION FOR AUTOMATIC GENERATION OF CUTTING TOOLS TRAJECTORIES ACCORDING TO THE GIVEN CRITERIA

L. PŁONECKI, W. TRĄMPCZYŃSKI, W. GIERULSKI, J. CENDROWICZ, K. SOKOŁOWSKI

KIELCE UNIVERSITY OF TECHNOLOGY

Al. Tysiąclecia Państwa Polskiego 7, 25–314 Kielce

The computer control system for heavy machine (loaders, excavators) fixtures motion is presented and discussed in the paper. It enables the automatic generation of cutting tool (buckets) trajectories to fulfil the assigned criteria, for example the minimum unit energy criterion or the maximum disposable force criterion. The performance of the system was investigated using the laboratory stand built in semitechnical scale and the model cohesive soil. The tool shape in the stand corresponds to the shape of the bucket of the Waryński excavator K-111.

1. Introduction

The earth cutting process and the tool filling process of heavy machine tools is a strongly nonlinear dynamic process, which can not be precisely "manually" controlled by the operator. On the other hand, modern technical requirements and economical aspects force the soil cutting to be more and more precise and economical. Hence, several systems have been implemented, assisting the operator in more accurate control of the heavy machine fixtures motion. For example, the laser-type reference system for automatic or visual control of the digging process for the excavators can be mentioned here.

The systems have been also proposed to realise automatically more complicated motions, according to the given criteria. It is worth to mention the computer control system [1, 2] which enables a fully automatic work of the backhoe excavator and the simple hydraulic system [3, 4] to keep automatically the maximum permissible cutting force (such a system assures the operator safety and enables him to accomplish the work in the shortest time – the machine cannot roll over, but the energy consumption is not taken into account).

The second solution was based on the idea to keep the oil pressure in the fixture cylinders between the prescribed limits. Although it was a very simplified system, it allowed for the excavator to increase the digging efficiency by about 20% and to lower the tool force oscillation. In spite of such promising results, this system was used only in some prototype machines and was not further developed. Because of its simplicity, the system did not allow to keep precisely the maximum permissible cutting force.

In spite of the undertaken efforts mentioned above, there are no available systems that can ensure the tool motions according to the given criteria. It concerns such tool motions as the motion along the trajectories with minimum unit energy, or the trajectories with maximum disposable force with respect to the machine statics.

The cutting tool trajectories, meeting the different criteria, can be realised by means of the numerical control system. Such a system, designed to assist the operators of hydraulic excavators, was built on the basis of PC computer having D/A and A/D converters and its usability was proved [5, 6].

This control system has been generally described in this paper. Then the modification of the system and its application to generate the tool motions along the trajectories with minimum unit energy and the trajectories with maximum disposable force – are presented here.

2. Numerical control system characteristics and description of the laboratory stand

The control system of the heavy machines fixtures motions [5, 6] utilises the control system of the hydraulic cylinder positions and forces acting in these cylinders. It can be controlled by the proportional hydraulic valves fed by the variable output multi-piston pump, as in the stand described below, or by the electro-hydraulic servovalves. The PID numerical controllers have been used to control the cylinder displacement.

The control system, which operates using the interruption system of the computer, and the synchronisation of the motion of the individual fixture cylinders, necessary for the cutting tool trajectory determination, has been installed for this purpose.

Experiments carried out on the backhoe excavator K-111 fixtures prove [5, 6] that this control system meets all the foreseen requirements and can be used as the assisting unit of the machine operator. It enables the precision guidance of the tool, proper realisation of its required trajectories and automatic repetition of the motions made.

The modification of this system is described in this paper, to match the special laboratory stand and to generate automatically the cutting tool trajectories according to such criteria as:

- the minimum unit energy criterion, and
- the maximum disposable force criterion.

Next, the proposed procedures are checked on this stand.

The laboratory stand [7, 10], built in semi-technical scale system, consists of a container filled with model soil. Models of heavy machine tools move within this soil, then kinematics and forces acting on operating tools are observed and recorded (Fig. 1) there.

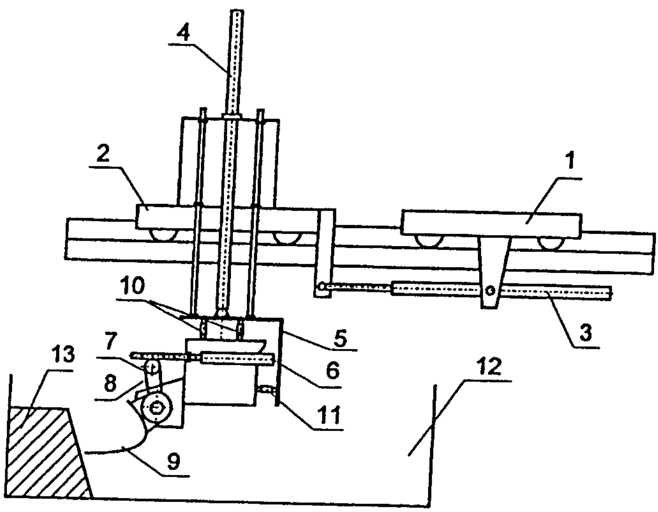

FIG. 1. The laboratory stand: *1*. Rear frame, *2*. Horizontal movable frame, *3*. Horizontal hydraulic jack, *4*. Vertical hydraulic jack, *5*. Vertical movable frame, *6*. Rotation hydraulic jack, *9*. Model of a tool, *10, 11*. Loading chambers, *12*. Container with transparent wall, *13*. Soil.

Displacement of the model tool (*9*) (the bucket of an excavator) results from the sum of three motions:

- horizontal motion of the front carriage (*2*), realised by the hydraulic cylinder (*3*) (while the rear carriage is blocked),
- vertical motion of the frame (*5*), realised by cylinder (*4*), and
- rotation motion of the tool, realised by cylinder (*6*).

The tool model is fixed to the rigid frame (*5*) through the set of loading chambers (*10, 11*) that enable us to make the measurements of horizontal and vertical force components. The force acting on the cylinder being responsible for the tool rotation (*6*), is measured directly at the piston rod. The tool displacement is measured by three extensometers of rotational type, equipped with reducers.

The model tool moves within the container (the plane strain conditions) with one transparent wall, which enables the observation and photographic recording of the material deformation during the tool cutting and filling process.

The control and measuring system was built using the PC computer having D/A and A/D converters. As it was mentioned, the control system for cylinders is based on three control subsystems; each of them is designed to control a different cylinder displacement, using PID controllers. It enables to control the tool motion by the measurement of forces acting on the tool and by the measurement of the cylinders displacements. The PID controllers are of such a type that their over-regulation range is $5 - 10\%$.

The planning system of the cutting tool trajectory [8] enables in particular:

- realisation of the prescribed trajectory for different starting points,
- realisation of the prescribed trajectories defined by the nodal points in the operating area,
- easy creation of different trajectories for different tests,
- application, when the prescribed motions occur, of the system to control the tool displacements, velocities and acting forces,
- realisation of the conditional motion, needed for branch structure programming,
- realisation of the full sequence of motions, previously prescribed.

The tool trajectory planning is realised with the use of the operator screen presented in Fig. 2. Each row of the presented table defines the interval of the tool motion. In the following rows, the values characteristic for cylinder motion (of horizontal, vertical and rotational type), such as: velocity, acceleration, force, signal from the manual controller and stand-by signal (with its stabilisation) can be defined. The last row of the table shows the condition of transitions from one set of parameters to another. These conditions can be defined as the values related to the positions or velocities of particular cylinders and values of the acting force components. The co-ordinates of the cutting tool position and the value of the cutting tool angle, calculated as a simple, or reverse kinematics task - can be considered as such conditions.

It is possible to define several conditions independently of the defined row, what allows the branched structure to be controlled and included / excluded.

If synchronised motions of some cylinders are necessary to be included there, it is possible to plan them, for example when the tool rotation around one point is to be made.

The experimental results show that the presented control system meets all the prescribed requirements and is easy to be operated.

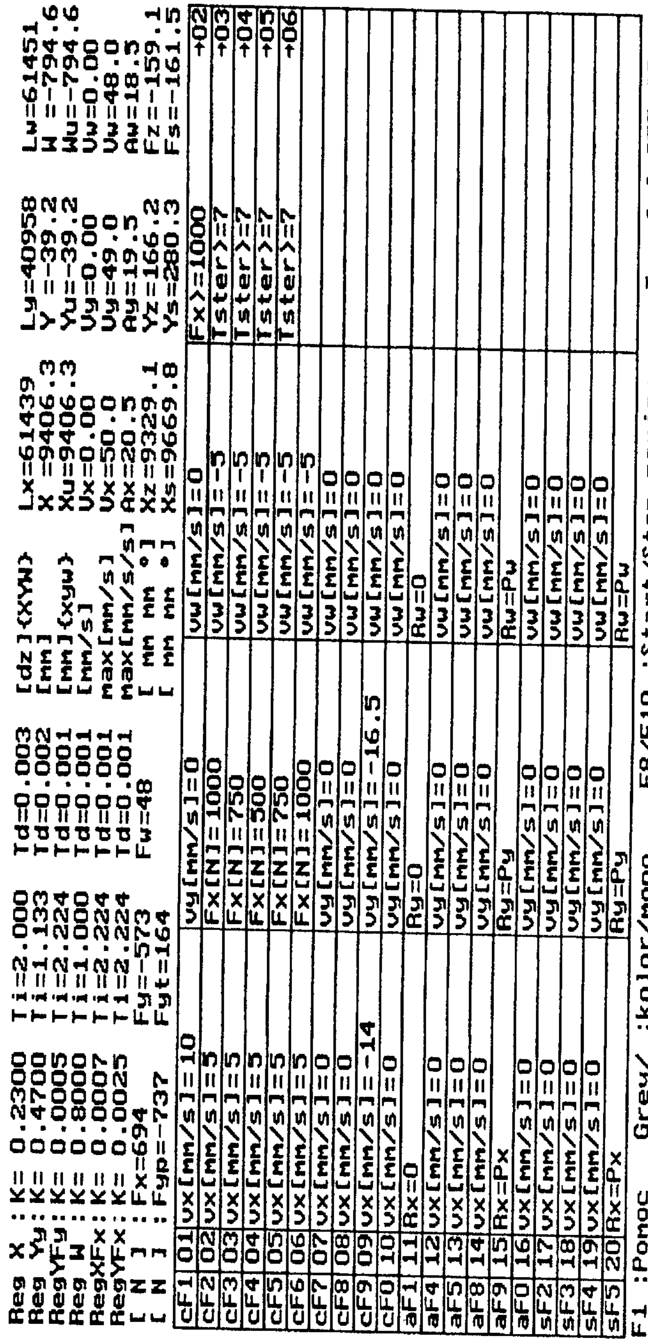

FIG. 2. The operator screen for trajectory planning.

3. The automatic generation of the energetically optimal tool trajectories

It has been confirmed [9, 10] that in case of earth movement, caused by heavy machine tools operation, the cohesive material deforms generating the rigid zones sliding along the slip lines, along which the tested material changes its characteristic parameters (decreasing its initial cohesion). The results of vertical wall pushing process show that the horizontal force increases – in an unstable way – as this process progresses. This observation confirms the earlier results [12, 13] concerning the slip line creation, during the plane wall pushing process.

The kinematically admissible solutions, based on the theory of plasticity for the plane strain conditions have been applied here, to describe the problem related to the advanced phase of the loading process of a heavy machine tool [9, 10]. It is assumed that the material to be tested (soil) is of Coulomb-Mohr type with softening. The results of the tests carried out under plane strain conditions confirm good correlation between them and the theoretical predictions. In this manner, we can describe such main effects of the earthmoving process as:

- the cohesive material deforms generating the rigid zones, sliding along the slip lines;
- along the slip lines the material substantially changes its cohesive properties decreasing the residual cohesion value almost to $c = 0$;
- in case of the simple tool pushing process for perpendicular wall, the relation: force vs. displacement shows that the horizontal force value increases in unstable manner. The force reduction coincides with creation of a kinematic mechanism, originating from the end of the tested wall.

The analysis of the test results and theoretical calculations show that when slip lines are created within cohesive material, the most effective way (from the energetic point of view) of the tool filling is to follow the previously created slip line where the material cohesive properties decrease.

One of the test [9] is presented in Fig. 3, as an example.

At first: the L-shaped tool was pushed into a cohesive soil ($c = 20$ kPa, $\varphi = 24°$), inclined at an angle $\lambda = 20°$, to a certain position (so-called pushing phase). When the tool was advancing, the slip lines were created periodically from the tool end to the free boundary of a material, at an angle $\alpha = 45°$. Then (so-called withdrawal phase) the tool end was moved along different straight lines (Fig. 3 – AD, AC, AB inclined at angles 30°, 40°, 50°), with simultaneous rotation of the tool, to be filled with the material.

The specific energy of such filling process, related to the lateral surface of the moved material (plane strain condition) W_f and the material left in the bucket W_q, for different "withdrawal" lines is presented in Fig. 4. In the case of $\alpha = 30°$

trajectory, the specific energy is much higher than for $\alpha = 40°$ and $\alpha = 50°$. Hence, by leading the tool end along the line inclined at the angle similar to the angle of slip line inclination ($\alpha = 45°$), the specific energy of earth-filling process can be significantly reduced.

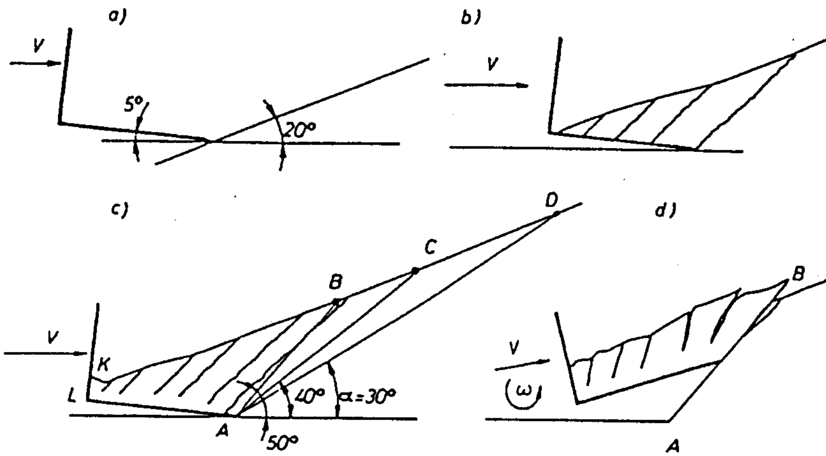

FIG. 3. The following phases of the tool filling process [9].

In all the test the existence of a "limit withdrawal angle" was established which coincides with the inclination of the outer slip line created during the "pushing phase". The tool filling process where the end of the tool, during the "withdrawal phase", moves along the line inclined in the "limit withdrawal angle", can be assumed as energetically optimal.

For the "withdrawal angle", lower than limiting one, the specific energy of the filling process substantially increases. For higher ones, the specific energy is similar to that for the "limiting withdrawal angle", but the amount of material, moved or left in the bucket, decreases.

It was also shown that for different trajectories, the two-stage type linear trajectories, consisting of the horizontal "pushing phase" and the "withdrawal phase" along the line inclined at an angle equal to the inclination of slip lines, are the most effective from the energetic point of view (Fig. 5a – OAB trajectory).

The experimental results, partially presented above, were obtained for the homogeneous cohesive soil. In such a case, the slip lines created in the material were straight ones and possible to predict. Hence, the tool trajectories, including the optimal ones, were precisely determined and planned as well.

In practice, because of the soil non-homogeneity and difficulty in definition of the slope shape, it is almost impossible to define the slip line shape and its position in advance. It can also happen that the slip line is not created during the "pushing phase".

Hence, the aim of following experiments was to use the control system described above and to create the procedures enabling:

- automatic generation of the slip line system in the material,
- automatic detection of a slip line,
- automatic drive of the tool end along the created slip line during the tool filling process.

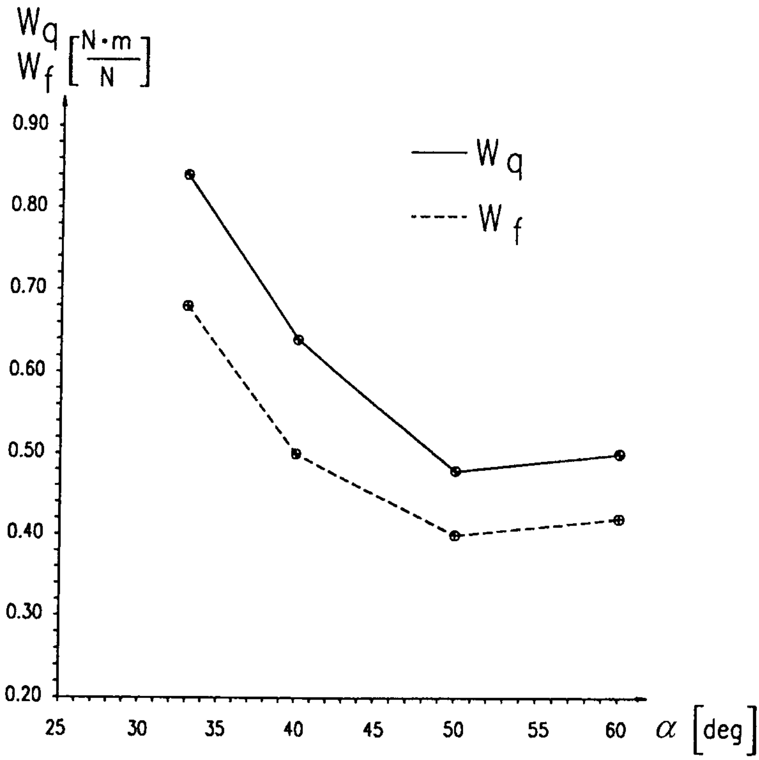

FIG. 4. Values of the unit work for different inclination of the "withdrawal" lines [10].

This way, the energetically optimal tool trajectories can be realised automatically.

The control system presented in [11] was then modified and a special procedure, described below, was proposed and verified.

The cutting tool motion is realised as the sum of horizontal, vertical and rotational movements. The horizontal pushing force is measured and used as a signal to control the tool motion.

Firstly, the tool moves horizontally until the horizontal component of the pushing force becomes equal to the assumed value F_1, or when horizontal displacement of the tool Δx is achieved. In this manner, the horizontal "pushing phase" is realised (as in Fig. 3b).

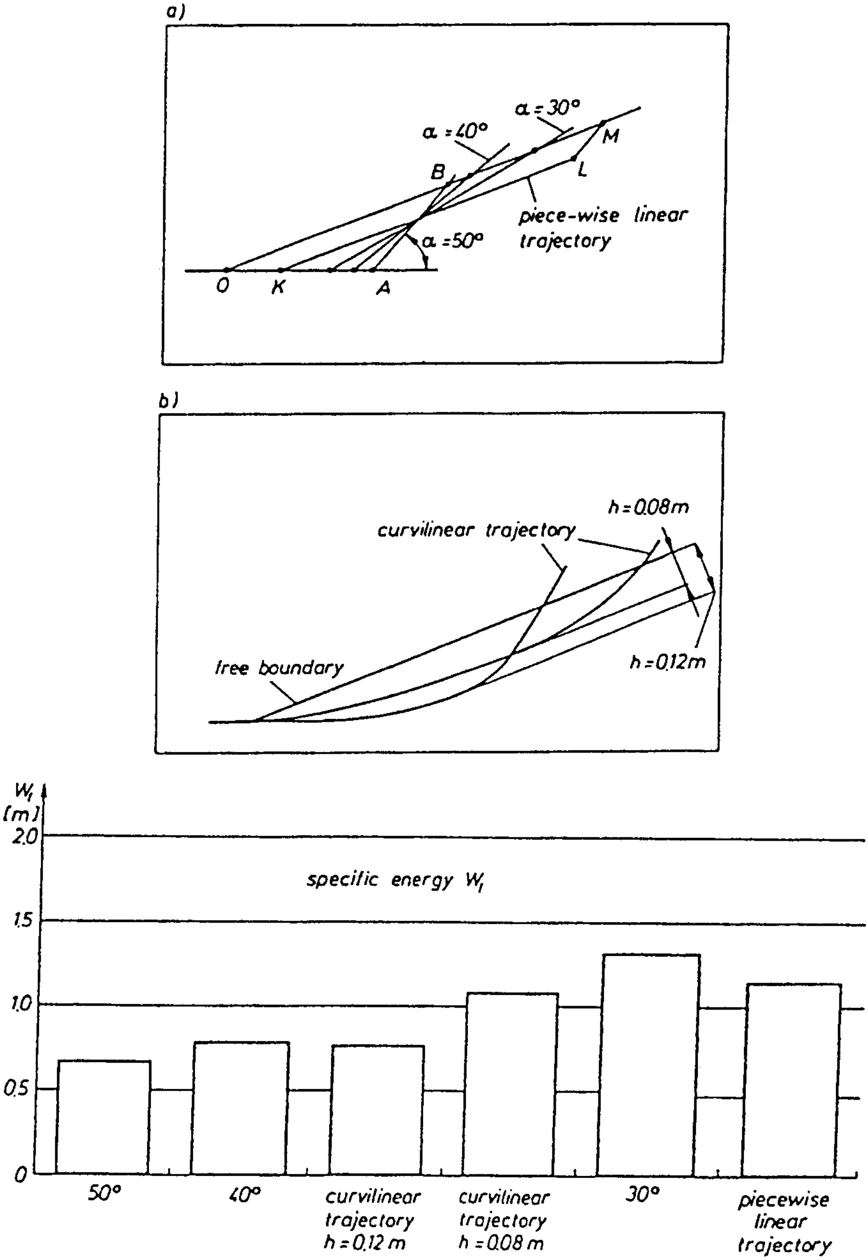

FIG. 5. Different tool trajectories and corresponding values of the unit work [9].

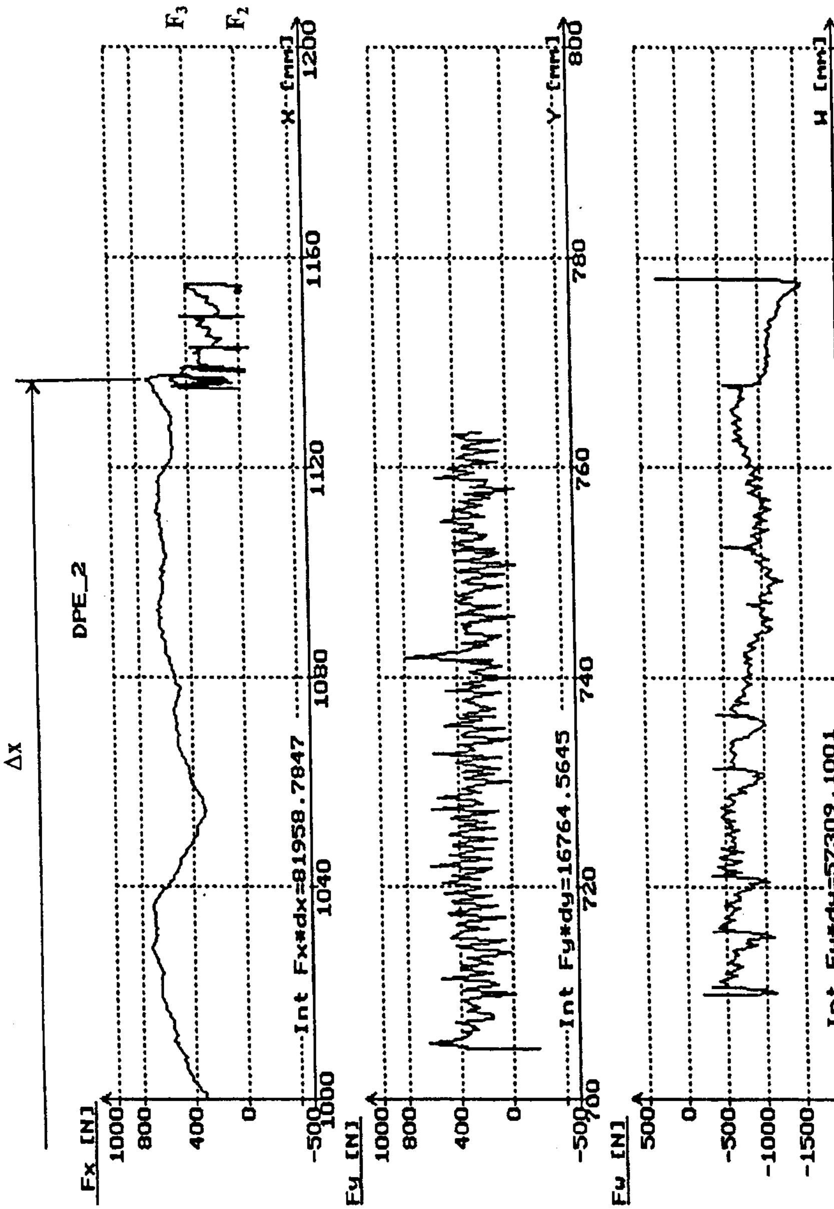

FIG. 6. The force vs. displacement for three cylinders in case of automatic tool movement along the slip line.

Next the tool stops and rotates by the prescribed angle α. This movement creates the slip line originating from the tool end.

Then the tool moves horizontally backwards until the horizontal component of the pushing force reaches F_2.

Afterwards, the tool moves vertically by prescribed displacement value and rotates by the prescribed angle α_1 as well, then moves again horizontally until the horizontal force starts to increase and exceeds another value F_3.

Then the tool stops and moves horizontally backwards until the horizontal component of the pushing force is equal F_2 and so on...

It was proved that for properly defined values F_3 and F_2, the tool moves gradually along the slip line, where the substantial decrease of the material cohesion appears (without significant tool penetration into the original material). The tool rotation allows to fill it during the process operation.

The tool filling process is observed by the operator, who decides when to stop the automatic filling and change to the manual control. The tool is then manually unloaded and moved to the starting point. Hence, the described automatic filling system can be used as the machine operator assistance.

The results of one of the experiments (where the "pushing phase" was defined by the horizontal displacement $\Delta x = 160$ mm) are shown in Fig. 6, where the horizontal force, vertical force and torsional force vs. appropriate piston displacement are presented.

The horizontal control forces $F_2 = 50$ N and $F_3 = 380$ N have been chosen here. It was found that for such data, the tool end follows the previously created slip line. These forces recorded in Fig. 6 diagram are slightly different because of the system inertia.

4. Automatic generation of tool trajectories for the prescribed cutting force

When the tool cutting and filling process progresses, the pushing force changes substantially, especially for non-homogeneous soil [3, 4]. Forces acting on the tool should not exceed certain values due to machine statics (when the force is greater, the machine can roll over).

Introduction of the digital control systems for heavy machines allows for easy detection of the fixture configuration and determination of maximum disposable forces that are calculated "on line". The precise control of the tool motion, regarding the maximum admissible force, can be realised by introducing special procedures to the fixture control system.

Three types of such procedures for the automatic tool movement with a prescribed force have been prepared there. The allowable maximum force alters when the fixture position changes and it can be calculated from the machine statics.

To simplify the tests carried out on the laboratory stand, it was assumed that only the horizontal component of the acting force will be controlled and kept constant.

In the first procedure, the tool moves horizontally until the horizontal force reaches the defined value F_1. Then, the tool is moved vertically by the prescribed displacement value and rotates until the horizontal force reaches another value F_2. Then the tool moves horizontally until the horizontal force reaches the defined value F_1.

By repeating such a loop, the tool trajectory with horizontal force that does not exceed the prescribed value (F_1), can be generated.

The second procedure is based on utilisation of the horizontal force control system. As before, the tool moves horizontally until the horizontal force reaches the defined value F_1. Then the horizontal force regulation system is switched on and continuous vertical motion of the tool, with rotation, starts with assumed cylinders velocities. The horizontal displacement results from the operation of the horizontal force regulation system.

In the third procedure, the regulation system of the vertical cutting force component is used and the horizontal component of this force is used as the control signal. The tool moves horizontally until the horizontal force reaches the defined value F_1. Then the tool rotates and moves continuously forward. The horizontal displacement is controlled to keep the assumed value of the horizontal force F_1 during this system operation.

The procedures mentioned above allow for the automatic tool motion with the prescribed and altering cutting force. The process of the tool filling, realised in this manner, is different from that described as the optimal one (Sec. 3). It is because the slip line is not created by the system at the beginning (the special rotation has to be applied for it), and because the control force F_1 simulates the maximum permissible force and has different value than the force chosen to follow the slip line.

In the following experiments, the tool trajectories were generated automatically as the result of motion of three cylinders (this motion was controlled by the system). It is also possible to apply such a procedure, where the motion of one or two cylinders is controlled manually (by the operator) and the motion of other cylinders is controlled automatically to keep the assumed criteria.

5. Examples of operation of the automatic control system

The experimental investigation of the control system was performed in a laboratory [5, 8], using the laboratory stand (plane strain conditions) and model soil ($c = 35$ kPa, $\varphi = 24°$, $\gamma = 18.4$ kN/m^3). The special procedure for the soil compact conditions ensures the soil homogeneity and the repeatability of the test results. The experiments were carried out for the model tool having the bucket of the excavator K-111 shape, made in 1:2 scale.

5.1. *Automatic tool motion along the slip line*

The automatic control system, described above, was then used to generate the energetically optimal trajectories of the tool filling. Different trajectories of the tool (including the automatic ones as well) were realised experimentally. The total energy (calculated as the summarised energy produced by the cylinders) for each process was measured and the unit energy for each process was calculated as the energy vs. lateral area of the excavated soil (Nmm/mm^2).

Different tool trajectories are presented in Fig. 7. The ABC trajectory was generated automatically in the way described in Sec. 3. The tool was moved horizontally to point B. Then the horizontal motion was stopped and the tool rotated by prescribed angle α creating the slip line, originating from the tool tip (BC). Then the tool moved horizontally backwards till the moment when the horizontal component of the pushing force was equal F_2. Next, the tool moved vertically by the prescribed distance and rotated by the prescribed angle α_1. Then it moved again horizontally till the moment when horizontal force started to exceed the value F_3.

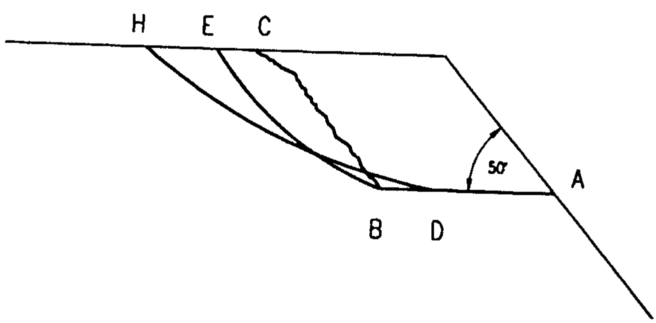

FIG. 7. Different tool trajectories: ABE and ADH – typical paths realised manually by the operator, ABC – The "slip-line" trajectory generated automatically.

This way the tool end moved along the slip line BC till the moment when it crossed the soil free boundary (C). According to the former experiments [9, 10], such a trajectory (where the tool end follows the slip line) should be energetically optimal.

Two other paths (ABE and ADH) represent the typical paths realised manually by the machine operator and they were previously planned.

The average unit energy (based on at least three experiments) for these trajectories is presented in Fig. 8. The trajectory created automatically, in the way described above, was realised with the lowest unit energy (30% less than for other trajectories) and allows for substantial energy saving.

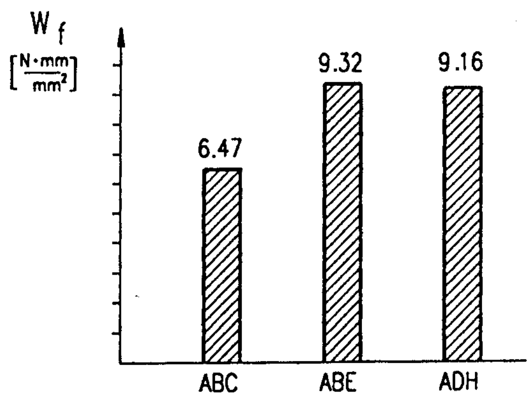

FIG. 8. The average unit energy for trajectories presented in Fig. 7.

Let us discuss now quite a typical problem of soil excavation when the soil slope is formed (Fig. 9a). The prescribed quantity of soil has to be dug out from the slope inclined at an angle 50°.

Different tool trajectories realised by the machine operator himself or with the use of simple control systems are presented in Fig. 9b-e:

• The horizontal scarping (Fig. 9b); the cutting tool (inclined at an angle 5°) moves horizontally, cutting the thin layer of the soil (5 cm), along the prescribed length. Then, the horizontal motion stops and the tool withdraw along the line inclined at an angle 50°.

• The scarping along the slope (Fig. 9c); the cutting tool (inclined at an angle 5°) moves along the slope, cutting the thin layer of the soil (5 cm), till it reaches the soil free boundary. The bucket shape digging (Fig. 9d); the cutting tool (inclined at an angle 5°) moves horizontally penetrating the slope to the assumed displacement value. Then the horizontal movement stops. The tool rotates and moves vertically till it reaches the soil-free boundary.

• The bucket shape digging (Fig. 9e) for non-typical free boundary shape (for example such a free boundary results from the previous digging); as before, the cutting tool (inclined at an angle 5°) moves horizontally, penetrating the slope to the assumed displacement value. Then the horizontal movement stops. The tool rotates and moves vertically till it reaches the soil-free boundary.

Figures 9f, g show the trajectories which were realised automatically, with application of the procedure described in Sec. 3. Such trajectories were chosen, taking into account the results presented in Figs. 7 and 8. The material was excavated from the "top" to the "bottom", a sequence of the automatic motions mentioned above (Fig. 7 – trajectory ABC). The thickness of the excavated layer and the range of the horizontal tool movement are chosen to fill the tool.

The trajectories presented in Figs. 9b-e were previously determined, while the trajectories presented in Figs. 9f, g were generated automatically. The total energy for different processes was measured and the unit energies were calculated as well.

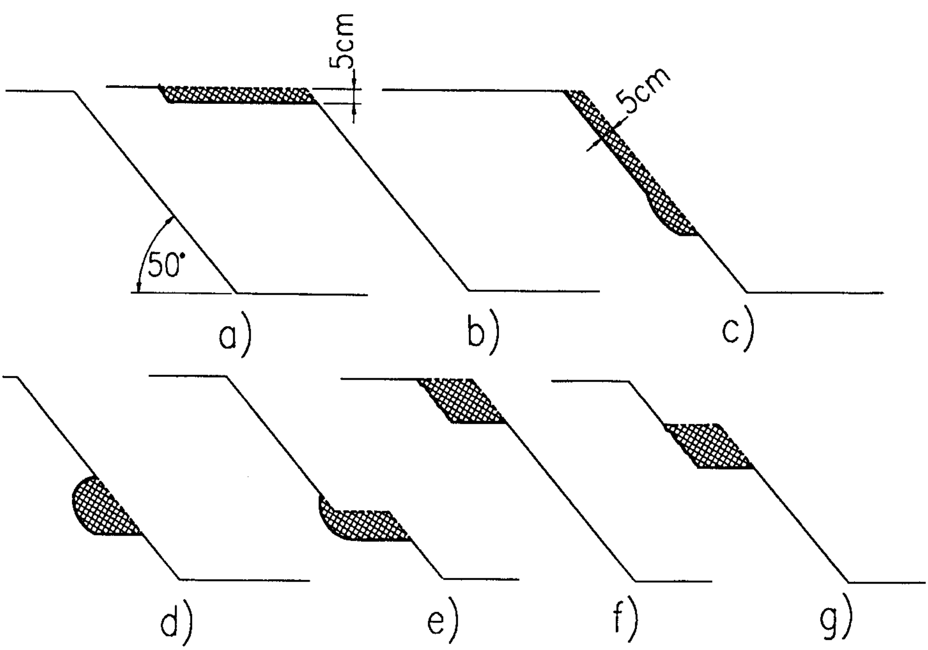

FIG. 9. The trajectories of different tools.

Fig. 10 shows the average unit energy for different trajectories.

The unit energy for the tool trajectory generated automatically (Fig. 11g, f) is the lowest one (6.68 $\mathrm{Nmm/mm^2}$).

The unit energy for the horizontal scarping (Fig. 10b) is 32% higher and equal to 8.82 $\mathrm{Nmm/mm^2}$. Such a tool motion is not performed by real machines and is presented here as an example only.

However, the unit energy for the earthmoving from the scarping along the slope is almost two times greater (Fig. 10c, 13.03 Nmm/mm^2) than the unit energy for the proposed automatic motion.

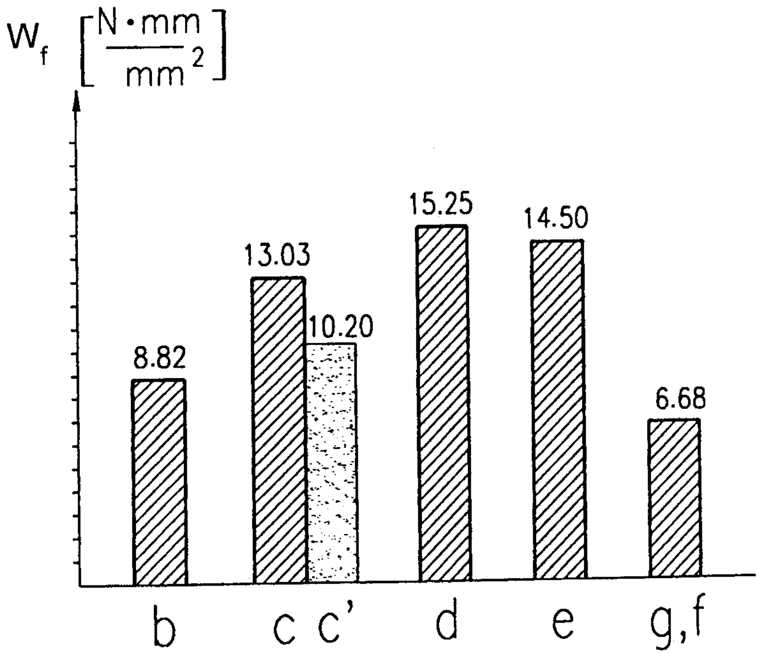

FIG. 10. The average unit energy for trajectories presented in Fig. 9.

It is worth to mention that this energy level is greater than in the case of earthmoving for the horizontal scarping. One reason of this difference results from the fact that in this type of motion, the material is not only cut but also rised up (as high as the slope height). By subtracting the energy of such a motion from the measured unit energy for the earthmoving for the scarping along the slope, the modified unit energy value 10.2 Nmm/mm^2 is obtained. This value is close to the unit energy needed for the horizontal scarping (16% greater) and about 53% greater than the unit energy for the proposed automatic motion. It should be also mentioned that the tool trajectory presented in Fig. 9c is not exactly parallel to the slope, what can increase additionally the unit energy.

This result coincides with the results of very precise experiments for different tool trajectories [14]. It was proved that the unit energy for the tool trajectory similar to that presented in Fig. 9g is substantially lower than that for the horizontal and slope scarping.

The unit energy for the bucket shape digging (Fig. 10d, e) is more than two times greater than the unit energy for the proposed automatic motion.

The test results show that the proposed automatic motion, where the tool end follows the previously generated slip line, is energetically most advantageous. This way the energy for the cohesive material excavation can be substantially reduced in relation to the manual control.

5.2. *Excavation with assumed cutting force*

The results of the system operation in case of excavation with assumed cutting force are shown in Figs. 11-15. The tests have been carried out for different slope inclinations and for different control parameters – only to show the performance of the system.

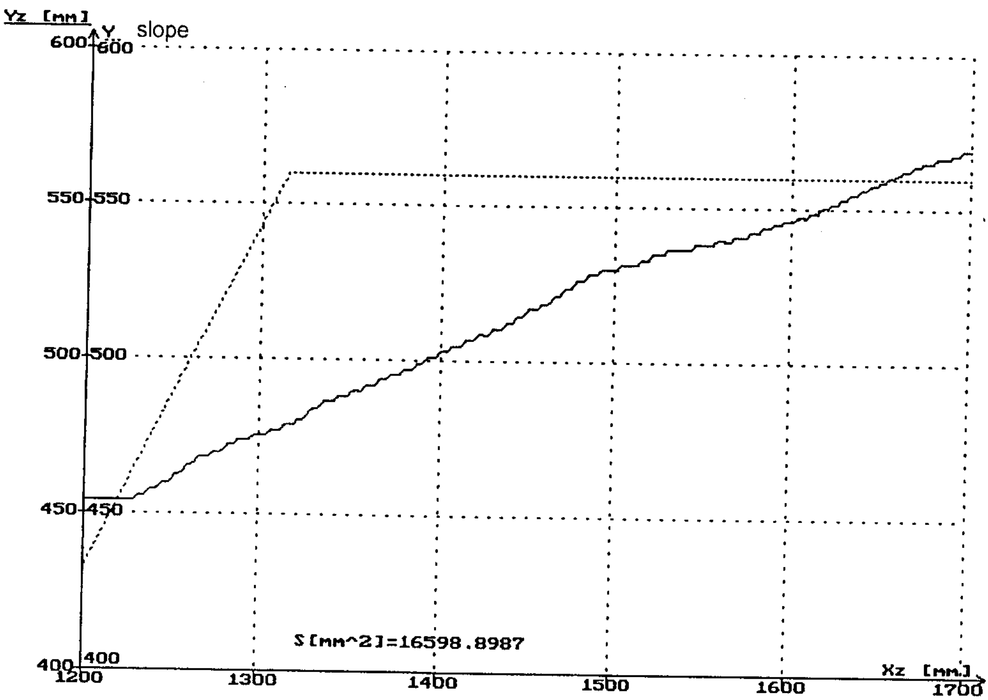

FIG. 11. The tool trajectory, the profile of the soil slope (dotted line) in case of excavation with the assumed cutting force (first procedure).

For example, the tool trajectory generated automatically by the system using the first procedure – as mentioned in Sec. 4 (where the slope inclination was 50° and $F_1 = 500$ N, and $F_2 = 400$ N were assumed) is presented in Fig. 11.

In Fig. 12 and 13 are presented the tool trajectories, also generated automatically by the system, where the horizontal (Fig. 12) or vertical (Fig. 13) cylinders

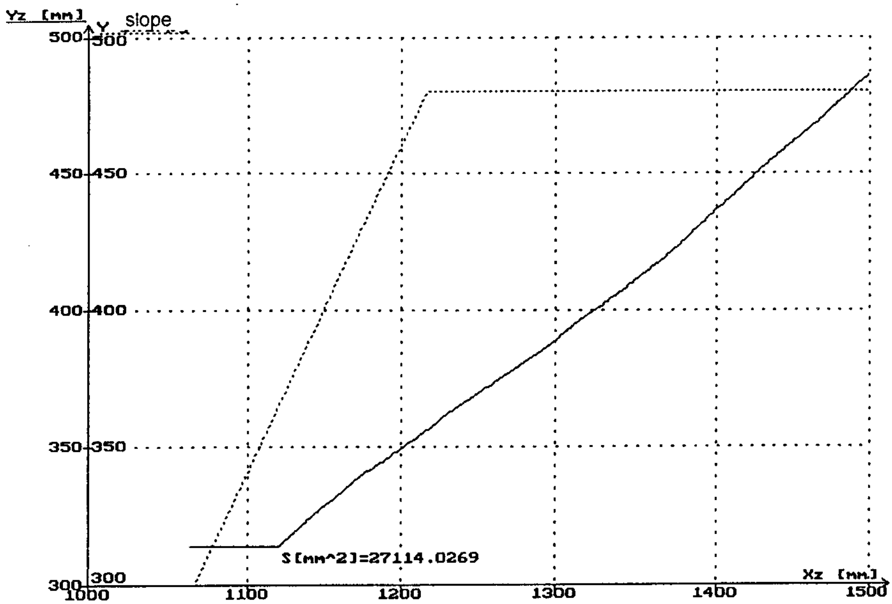

FIG. 12. The tool trajectory and the profile of the soil slope (dotted line) in case of excavation with the assumed cutting force (second procedure).

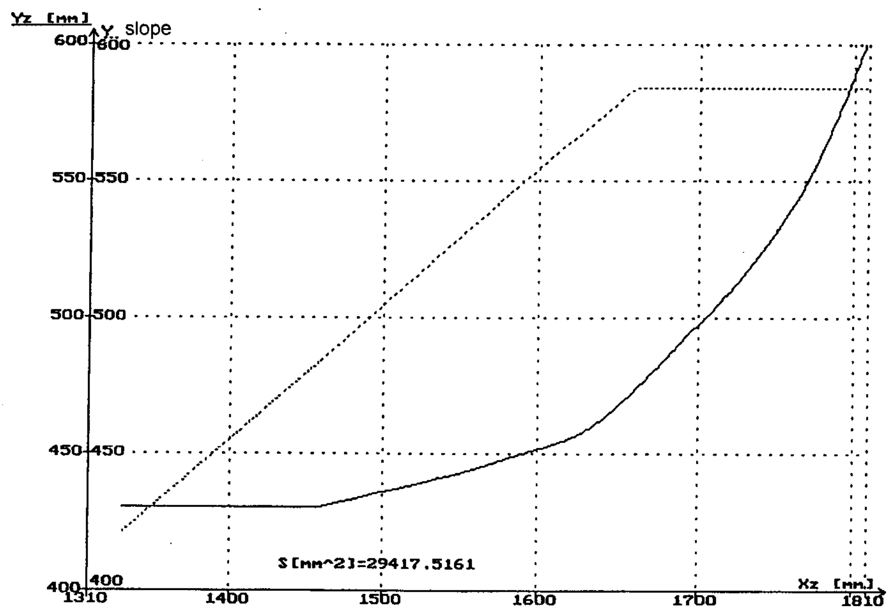

FIG. 13. The tool trajectory and the profile of the soil slope (dotted line) in case of excavation with the assumed cutting force (third procedure).

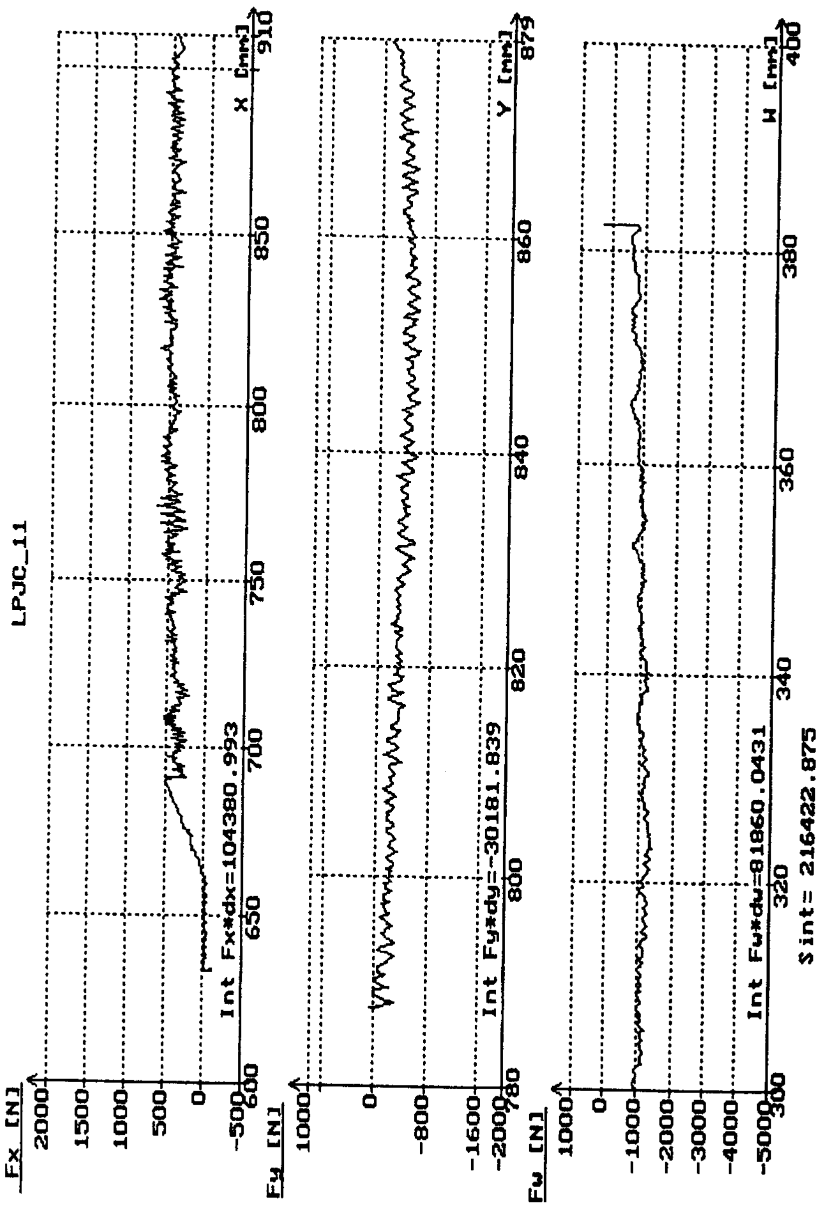

FIG. 14. The force vs. displacement for three cylinders for the trajectory presented in Fig. 12.

are controlled (the second and third procedure). In Fig. 14 are shown the values of the horizontal (F_x), the vertical (F_y) and torsional (F_w) forces vs. the cylinder displacement for the trajectory presented in Fig. 12.

The example of the system operation, when the variable cutting force is assumed, is presented in Fig. 15. The procedure described as the third one in Sec. 4 was applied here. The prescribed horizontal cutting force was changed gradually every 7 seconds, assuming the following values: 1000 N, 750 N, 500 N and 750 N. The operator screen with data to plan such a trajectory is shown in Fig. 2.

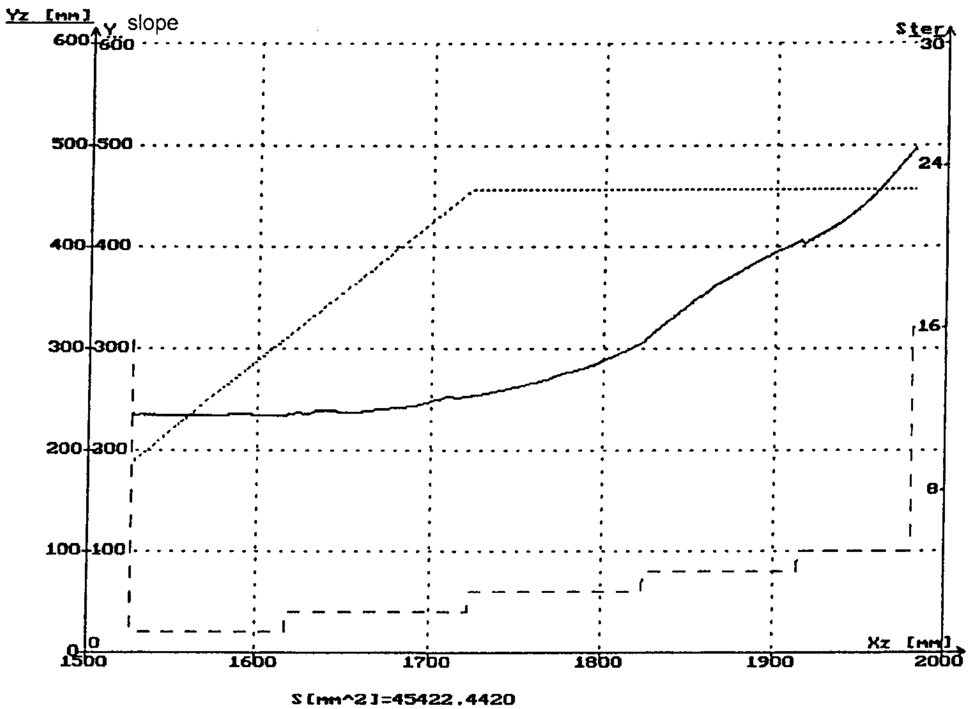

FIG. 15. The tool trajectory and the profile of the soil slope (dotted line) in case of excavation with variable cutting force.

6. CONCLUSIONS

The results of the above experiments show that the presented control system for heavy machines fixture motion meets the requirements concerning all the prescribed parameters and enables the automatic generation of cutting tool trajectories according to the given criteria.

The presented control system, which ensures the tool-end to follow automatically the previously generated slip line, enables the automatic creation of the cutting tool trajectories being optimal from the energetic point of view. It is experimentally proved that the unit energy of the tool filling process, when such a system is applied, is substantially lower than other typical trajectories.

The proposed control system allows also to carry out the excavating process with the prescribed and variable cutting force. It enables the excavation to be carried out with maximum permissible force, being continuously calculated for the given fixture position. The tool motion along the trajectories of the maximum possible force, assures the operator's safety, enables the work to be done in the shortest time and increases the machine efficiency as well.

The control system and the procedures of its operation were experimentally examined, with use of the laboratory stand, where the tool motion resulted as the sum of horizontal, vertical and rotational motions. Because it was proved that the soil deformation pattern for the motion created in this way is similar to that which occurs in real conditions of an excavator operation, the presented control system can be used and treated as the real machine control system, to assist the operator.

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References

1. D. A. Bradley, D. Seward and F. Garas, *Towards side 2000 – development in automation and robotics in construction*, Proceedings of 8th International Conference of the ISTVS (The Intern. Society for Terrain – Vehicles Systems), **1**, 1991.

2. A. N. B. Ahmad, J. N. Scott and D. A. Bradley, *Task decomposition in support of automation and robotics in construction*, Proc. of 12-th Int. Symposium on Automation and Robotics in Construction (ISARC), 1995.

3. Z. Bogusz, *Investigation and evaluation of electrohydraulic control system in K-408 excavator* [in Polish], Reports of the Building Mechanisation and Mineral Mining Research Institute, Warsaw 1975.

4. Z. Bogusz, *Automatisation of the cutting process for universal excavators* [in Polish], Mechanical Review, **29**, 7, 1970.

5. L. PŁONECKI and J. CENDROWICZ, *A concept of the assisting system for the hydraulic excavator operator* [in Polish], Proc of X Conf. "Problems of Working Machines Development", Zakopane 1997.

6. L. PŁONECKI, W. TRĄMPCZYŃSKI and J. CENDROWICZ, *A concept of digital control system to assist the operator of hydraulic excavator*, Automation in Construction, 7, 1998.

7. J. CENDROWICZ, W. GIERULSKI, L. PŁONECKI and W. TTRĄMPCZYŃSKI, *The laboratory stand for the soil shoving processes due to an excavator bucket* [in Polish], Proc. of III Conf. "Experimental Methods in the Building and Exploitation of the Machines", Wrocław - Szklarska Poręba 1997.

8. L. PŁONECKI, J. CENDROWICZ, W. GIERULSKI and W. TRĄMPCZYŃSKI, *On the trajectory planning for the robotised, laboratory, soil shoving machine* [in Polish], Reports of the Institute of Technical Cybernetics, Politechnika Wrocławska 1998.

9. A. JARZĘBOWSKI, J. MACIEJEWSKI, D. SZYBA and W. TRĄMPCZYŃSKI, *On the energetically efficient trajectories for the heavy machine shoving process*, Eng. Trans., **43**, 1–2, 1995.

10. A. JARZĘBOWSKI, J. MACIEJEWSKI, D. SZYBA and W. TRĄMPCZYŃSKI, *The optimisation of tool shapes and trajectories in heavy machines*, Proc of 12-th Int. Symposium on Automation and Robotics in Construction (ISARC), 1995.

11. J. CENDROWICZ, W. GIERULSKI, L. PŁONECKI and W. TRĄMPCZYŃSKI, *The computer system for the optimal cutting tool trajectories on the basis of the cutting force measurement* [in Polish], Proc. of XI Conf. "Problems of Working Machines Development", Zakopane 1998.

12. Y. HATAMURA and K. CHIJIIWA, *Analysis of the mechanism of soil cutting*, (Reports 1–5), Bulletin of the JSME, **18**, 120, 1975; **19**, 131, 1976, **19**, 137, 1976; **20**, 139, 1977; **20**, 141, 1977.

13. S. ISHIBA, K. HYODO and Y. OSHI, *A study on the mechanical behaviour of soil during flat edge cutting*, Mitsubishi Technical Bulletin, 176, 1987.

14. A. JARZĘBOWSKI and J. MACIEJEWSKI, *The optimisation of the excavation process* [in Polish], Proc. of XIII Conf. "Problems of Working Machines Development", Zakopane 2000.

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