Interaction between presses, tools and processes in metal forming

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Summary

The productivity of presses is mainly determined by the interaction of the various individual elements, like machine components, tool, workpiece, and process technology. A fundamental clarification of this interaction is necessary in order to establish a basis for systematic metrological and also theoretical analysis which allow an assessment of the important characteristics of the complete system. A foundation is thus created for the layout, correction and adaptability of the mentioned elements.

This paper presents the investigations of the relationship between press, tool and process technology. Special importance has been laid upon the determination of fluctuations of force amplitude as well as their influence on machine deformation and displacement which in turn determine the accurarcy of the workpieces and tool wear.

1. Introduction

The increasing demand for industrial products existing throughout the world can only be met in future if in the production process the technological reserves are utilized in a way that both raw materials and sources of energy are preserved. In this respect particularly the forming process offers advantages through the virtually free designing and shaping of workpieces and the contingent minimum of waste.

A drawback of forming processes may be the large lots that are generally required. To illustrate this statement figure 1 compares the costs of forming and cutting a tooth gear. The steep inclination of the cost curve for forming operation reflects the fact that the tool costs and setting-up costs are relatively high.

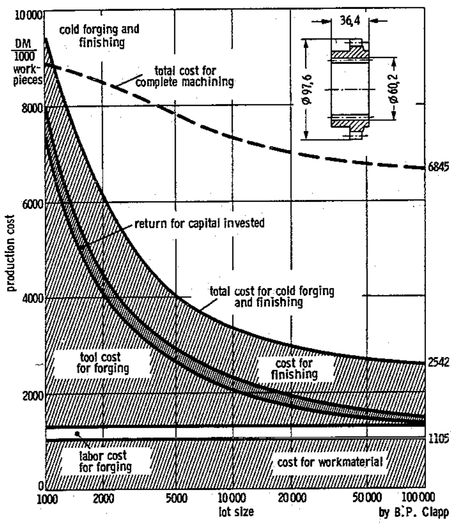


Fig. 1: Comparison of production cost

Another problem may arise from the fact that more and more public attention is turned to ecology and human aspects of labor. In comparison to many other metal processing operations forming processes can strongly affect the ambience of machines and the shop environment.

These are some reasons why forming asks for increasing flexibility. The flexibility of the production situation can be improved by research work. As far as forming is concerned, it is partly due to the extreme costs of large scale experiments and equipment that scientific results are less available than in other branches of production engineering.

We know little about tool life, how it depends on workpiece numbers, material properties, lubrication, machine behaviour, tool design. This stands for many other problems and shows that the forming process calls for a fundamental analysis of the interactions between process, machine and external factors.

2. Interactions between Process, Machine and External Factors

Every production system is composed of the elements process, machine, and external factors. The interactions of these elements are of different nature. Since they are extremely complex and do not occur on a physical level only, an analysis of the overall system must be based on a structural arrangement. For the field of forming technology this is illustrated in figure 2. In the first place the three elements process, machine and external factors can be seen.

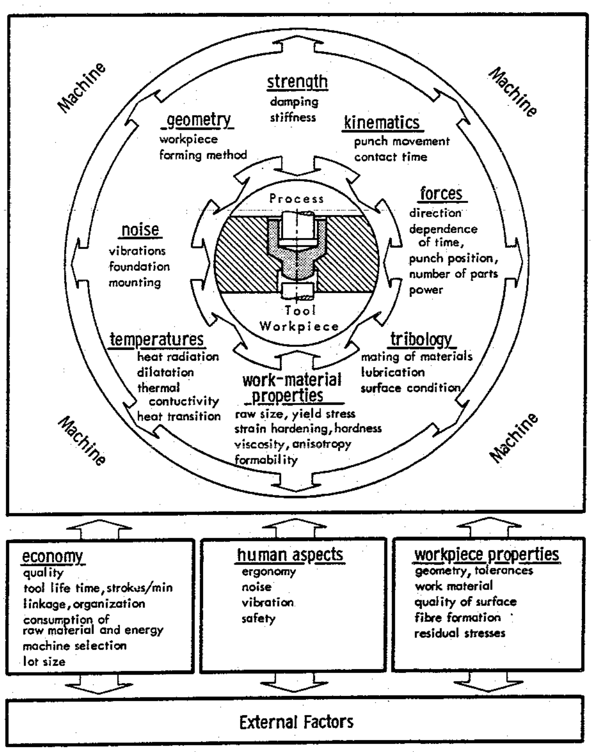


Fig. 2: Interaction between process, machine and external factors

The interactions themselves belong to various conceptual categories. These conceptual categories are arranged for taking into account that important interactions exist between the categories themselves. Apart from this it may be noted that the structure of the conceptual categories may be different subject to the scientific approach and the assignement to be accomplished.

The complexity of the whole system will now be illustrated by a few examples:

In forming technology the strength (see figure 2) of tool and machine is of major importance. Depending on size of workpiece, the material, and the deformation, plastic forming of metals requires considerable forces. As an example, the forging of a truck front axle will be taken. The forces required for this forming operation can easily exceed the 100 MN level. Thus a high demand has to be placed on the strength of tool drive, and frame.

Closely linked with the strength of tool and machine are their stiffness and damping. If dynamic effects are ignored for the time being, it is above all the stiffness which causes interactions. This can be illustrated by die forging with flash formation. In the final stage of the process, different forming forces can arise from the fact that due to a scatter in raw piece weights, different flash volumes have to be forced out. Constant measures of the finished parts can be maintained only if either machines and tool have a considerable stiffness in the working direction or the raw piece weights are kept closely under control.

Perpendicular to the working direction the flexibility of the structure will yield displacement and tilting of the ram. Both faulty shapes in the finished parts and overload of the ram guides can occur.

Particularly in die-forging of long workpieces minor differences in the distribution of the blank material cause considerable shift of forces.

Since an increase of the tilting stiffness will inevitably bring about an increase of the equipment costs, interaction with the external factor of machine selections arises. A rigid mechanical press featuring a wide working space offers the possibility of mounting several dies at the same time. In this way setting-up time is saved and smaller lots may be manufactured more economically.

Moreover, in certain cases only a non-tilting machine will meet the requirements of optimal automation. An example is forging with multi-step die. If the forming stages are suitably arranged, the workpiece is subsequently put into the adjacent die. The finish impression is always located at the end of the working space. Close production tolerances may be expected only if frame, guide and drive of the machine are designed in such a way that in case of eccentric loading satisfactory joining of upper and lower dies is guaranteed.

Also when dynamic problems are studied, the stiffness of machine, foundation, tool, and workpiece is a very important factor.

Vibration problems occur either at high stroke rates or when the force path characteristics of the process implies a sudden drop of force. In such cases the mechanical energy stored by the system machine-tool-workpiece during the built-up of forces is suddenly released, thus generating vibrations in the system. The vibrations of the components are either radiated in the form of noise or are conducted through the foundation into the ground. Thus dynamic effects may produce interactions, which will strongly influence both the process and the external factors.

As far as the process is concerned it is clear that the machine vibrations are transmitted to the tools and hence affect the course of forming.

Within the field of external factors, vibrations of the component parts will result in noise emission and concussions. It can happen that metal forming machines generate vibrations of 4 - 5 cp/s, so that adjacent buildings are exitated in natural oscillations. In such cases costly measures may seriously affect the economy of production.

On the shop floor noise is a serious problem. In the Federal Republic of Germany for instance a noise level of 85 dB(A) may be exceeded only if this is unavoidable for technological reasons. In view of this damping and stiffness are of essential significance. Within the cycle of forces of workpiece, tool and machine increased damping may result in improvement. For technological reasons, however, this can be utilised only to a limited extend, as damping and stiffness are closely interrelated, because an increase of damping will generally result in a loss of stiffness.

The characteristics of machine drive play a role when dynamical problems are studied. In general the process defines the power requirements as a function of tool speed and tool position. With machines, whose performance may be characterised either by motion or force requirement, drive may be designed in such a way that the forging tool will make contact with the workpiece at a relatively low speed. A reduction of noise may result.

After the tool has made contact, the interactions now occurring are primarily of technological importance. The deformation of the workpiece is brought about by the motion of the tool. This results in a direct interaction between ram motion, deformation of workpiece, tribology of the configuration material-tool-lubrication, as well as properties of the workmaterial.

In connectionship with the mechanical properties of the material thermal interactions should be mentioned too. Thus during the forging operation, temperature variations in the workpieces may lead to variations of the plastical properties, consequently of the forming forces. Interference of stiffness arises again and hence with the tolerances of workpiece measures. Thus the reduction in cost obtained by the use of a less stiff machine will be set back by the expenditure of control and inspection of the workpiece temperatures.

In the examples it was shown that there are many mutual interactions. For this reason an exhausting description of the system process-machine-external factors is strongly encumbered.

The lay-out of the system becomes much more clear if only the technical interactions are studied. In this case the interactions are of mere physical nature and hence a logical sequence of actions is present. This is shown in figure 3. The technical system consists out of the regions process, tool, machine, and ground. The region refering to the machine is devided in a more detailed way. Thus it is made plausible that in many cases the behaviour of the machine requires a separate analysis of the drive, the guidance and the ram system on the one hand, and the frame on the other hand.

In every region the physical properties which are relevant for the technical interactions are indicated. The arrows between the regions mean that the interaction originate from the process and next through the tool enter into the machine and finally influence the foundation.

The lower part of figure 3 describes the physical nature of the interactions and takes into account that interactions can directly influence the environment.

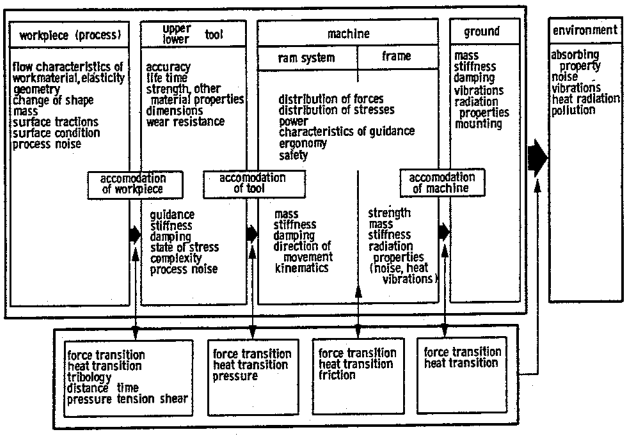


Fig. 3: Action sequence and properties of the elements process, tool, workpiece, machine and environment

In spite of good surveylability of the sequence of actions there are still so many technical interactions that it is necessary to analyse only groups of interactions. In the assessment of research goals it is necessary to know which part of the system deserves special attention. The answer of this depends strongly on the kind of present forming operation and can be found in the context of preliminary studies which can essentially depend on experience and logical analysis of the process. The special requirement on workpiece, tool, machine and environment can be determined. If these results are listed up an opportunity is offered to compare the different processes. As to this in figure 4 the procedure is shown for closed-die forging and stamping. Refering to the machine there are generally specific differences in machine construction. Also the process shows considerable differences. As an example the micro-texture of workpiece material is mentioned. It is relevant, when, as in blanking, a cutting tool enters into the material. In this case a favourable effect on wear can be obtained if globular cementite is present, which easily can be pushed into the softer ferrite matrix.

Similar examples can be found for other forming operations. In this way it is possible to complete the table in figure 4.

If goals for research have been determined interactions must be studied quantitatively. A feasible procedure for this is shown in the example of a simulation program for a controlled hydraulic press. The program is laid out for studying the mechanical interactions between process and machine behaviour.

		metal forming process										
		open die forging		closed die forging		extrusion		upsetting		drawing	deep drawing	blanking
demands	properties	w	k	w	k	w	k	w	k			
workpiece	geometry			○	●							●
	tolerances			○	●							●
	surface condition			○	●							●
	micro-texture			○	○							●
	yield stress			○	●							●
	strain hardening				●							○
	viscosity			●	○							
	directionarity											○
	formability			○	●							○
	heat conductivity			●								
	heat transition			●								
	residual stresses				●							
tool	rupture strength			○	●							●
	fatigue rupture strength			○	●							●
	wear resistance			○	●							●
	high temperature strength			●								
	tolerances			○	●							●
	complexity			○	●							○
machine	strength			●	●							○
	force			●	●							
	kinematics			●	○							●
	stiffness			●	●							●
	damping											●
	guidance precision			●	●							●
				●	●							○
environment (foundation) (building)	noise absorption			○	○							●
	vibration			●	●							●
	strength			○	○							
	space requirement			●	●							○

● important
○ less important

Fig. 4: Demands for the system workpiece-tool-environment

As can be seen in figure 5 an essential part of the program is the force loop. The right hand part shows the block diagram and explains the way in which the mechanical system is devided into subsystems.

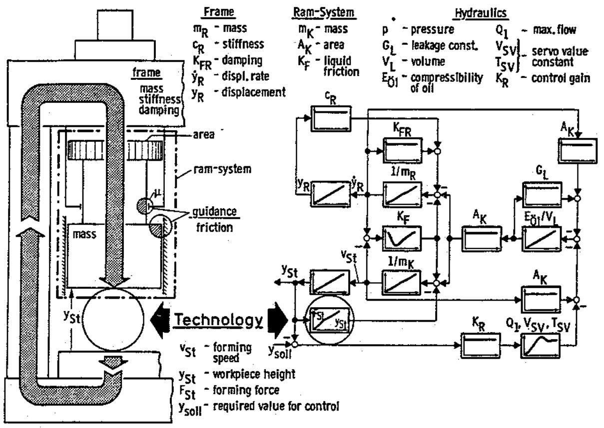


Fig. 5: Simulation of the system process-machine

For a specific case of simulation it is essential to find transfer functions for both, the technology and the machine components. For this reason we will next look on the means which are available to determine the process and the machine.

3. Means for the Analysis of Process and Machine

In the field of technology the first question is how to determine the process and the property of the product. Figure 6 gives an impression of the availability of technological means. In the rows physical properties are noted. In the columns we find the methods which can be applied to study the physics of workpiece and process.

	technological means to determine the process and evaluate the workpiece	evaluation of workpiece					process							
		strength	distorsion, cracking, residual stresses	fibre structure metallurgical structure	tolerances	surface quality	forces surface tractions	material flow kinematics	behaviour of work material	temperatures, heating, shrinkage	high pressure tribology	raw piece weight	stiffness	damping
experimental methods	measuring methods evaluation methods	●	●	●	●	●	●	●	●	●	○	●	●	●
	model testing similarity principles visioplasticity	●	○	●			●	●			○	●	●	○
solution catalogues	formulas nomograms	●	○		○	○	●	○	●	●	○	●	●	○
	data collections for flow curves and lubricants	●	●	○	○	○	●	○	●	○	○		○	
calculation methods	exact solution elementary methods sliplines upper and lower bounds	●	○	○		○	●	○		○	○	●	○	○
	difference methods method of weighted residuals finite elements	●	●	○		○	●	○		●	○	●	●	○
	thermodynamics crystalphysics physical-chemical	○	○	○		○	○	○	●	○	○		○	○

○ poorly developed ● available

Fig. 6: Availability of technological means

Firstly something has to be commented to the experimental methods. As far as the demands of the simulation program are concerned it is possible to measure the force-time characteristic and hence come to the transfer function for technology.

Leaving for a while the simulation program we have to state that knowlegde about forces is not sufficient for optimal adjusting the process. The analysis must be extended to physical mechanisms which take place within the workpiece.

Visioplasticity is one of the means which has been proved to be very successful in this respect. It makes it possible to study the flow of the material in detail and the process can be conducted in such a way that the workpiece obtains the desired course of fibres. Furthermore it can be determined whether in relation to the state of stress and the material used a certain degree of effective strain is not exceeded. If the experiment is completed with an algorithm also the state of stress can be determined. Through this it is possible to calculate the required forming force and power as well as the properties of the formed workpiece.

Since the experiments under real conditions often are very laborious or even quite impossible model experiments of forming processes are applied. The materials used in the model have a low yield stress but virtually simular rheological properties. The transfer of the experimental results of the model to the real situation is done by means of similarity physics. Here one gets easily aware of the limits of model experiments. If mechanical as well as thermal effects are to be taken into account and the tool is part of the analysis too, which implies eleven similarity conditions, it is impossible to obtain complete similarity.

If experimental methods because of extreme costs and poor reproducebility fail, a number of formulae nomograms and quick calculation methods are availabe to estimate the mechanical quantities of the process. However, in general these means rander average data only.

Returning to the requirements of the simulation program (see figure 5) a suitable method for determining the force characteristics of the process is the energy method of Fink. It allows to take into account any course of the flow curve and can be applied if realistic assumptions concerning the avarage value of the effective strain can be made. During the course of the program free upsetting was simulated. Here the effective strain can be calculated from continuity condition.

Although formulae can be used to estimate some mechanical properties they give little information about properties like structure, residual stresses or the onset of rupture. So the question is left to what extent mathematics can be applied to describe the plastic flow of metals.

From a mathematical point of view at first place plastomechanics is a boundary value problem. Difficulties arising in connection with the solution of the plastomechanic boundary value problem can be listed into three groups.

The first group concerns the boundary values themselves. The kinematical boundary condition in general are determined by the motion of tool. However, in order to define the static boundary condition difficulties are encountered since little is known about the friction between tool and workpiece.

An exception are some stationary forming processes where lubrication films are present. More or less in some drawing processes for example this assumption holds. The coefficient of friction can be calculated when the physics in the lubrication film is studied as a hydrodynamic boundary value problem.

In many forming operations the flow of material is non-stationary. Moreover the pressures between tool and workpiece are that high that a closed lubrication film cannot develop. This implies the description of the friction in relation to effects as elastic linkage, plastic ploughing adhesion and welding. Because of the extreme complexity of these phenomena it is hardly possible to predict a value for the coefficient of friction. For this reason the friction is commenly described by factores which are more or less obtained from shop experience and theoretical assumptions.

The second group of problems concerns the description of material properties and is due to the fact that most metals have a perfect memory as to their deformation history. A realistic description must provide the instantaneous flow stress as a function of strain rate, and histroy of strain. In case that also thermal effects are to be taken into account the difficulty is met that merely the complete formulation of the thermodynamic models requires the solution of a boundary value problem itself. However, if thermodynamics of the material is not considered the mathematical description of the material law is possible. Examples are the theory von M. Lévy and R. V. Mises.

The third group comprises mathematical problems which arise after formulation of the boundary value problem. Using the Levy - Mises theory one will meet a system of nine partial and one algebraic equation when general boundary conditions are introduced. An exact analytic solution of the system is possible only under the condition that the flow of the material can be determined uniquely from the motion of tool. However, these cases are rare and most of them are of academic character.
In order to analyse more general forming problems procedures have been developed which partly start from simpliffed conditions and use from case to case numerical algorithms. Some of the procedures became important in the field of forming technology and will be reviewed briefly.

The method of statical admissible slip lines is frequently applied. It is founded on the equilibrium of the material and makes it possible to determine the state of stress in plain and axisymmetric problems. Through extension of this classical method also the kinematics of the material flow can be considered to a limited extent. One of the disadvantages of statical admissible slip-line method is that it is only practicable for rigid plastic materials. Another disadvantage is that the forces and power obtained are less than the actual values and in fact they are a lower bound.

The influence of real material properties like strain hardening and viscosity can be investigated when the upper bound method is used. In the region of plastic flow a kinematical admissible velocity field describes the motion of the material. The state of stress and the upper bound for deformation power can be computed through the assumed material law. In principel any admissible velocity field can be applied and the state of stress derived from that is a criterion for the physical reliability of the assumed field.

An interesting possibility for numerical analysis of forming problems is the method of weighted residuals. Here both, the state of stress and the velocity field are described in free parameters. By optimizing computer technique the best fitting set can be optained.
Nowadays also the finite elements methode is more and more used to study forming problems. Anyhow application in the field of plasticity is far more difficult than in elasticity. In near future we will see, to what extent the method can be developed to a powerful mean for solving forming problems.

A computer aided simulation of the system forming process-tool-machine , as shown in figure 5, aims at describing the sequence of interactions between the seperate blocks of the system. This can only be successful, if besides the mathematical description of the forming process also the interaction between the components of the machine can be adequately described.

Comparable with the technological means which determine the forming process also the designer of the machine and tool disposes of a considerable amount of means to specify and to evaluate the properties of forming machines.

The relevant criteria to judge the properties of a forming machine are shown in the columns of the matrix of figure 7. The means availabe to the designer to evaluate the large number of properties are in the rows of the matrix. The figure shows that the availability of means varies according to the diverse properties being evaluated.

Aids available to construction engineers for determining and evaluating construction features	working accuracy and efficiency				behaviour of working place and environment			
	accuracy and kinematics of an unloaded machine	static behaviour	dynamic behaviour	thermal behaviour	acustic behaviour	vibrations	security	ergonomics
computation methods for design, post-calculations, optimization	◕	●	◕	◔	○	◔	◕	◕
measuring procedures for investigation of models, measurement of prototypes, serial measurements	◕	●	◕	◕	◕	◔	◕	◕
solution catalogues e.g.: principal solutions, construction catalogues, collection of solutions	◔	◕	◕	◔	◕	◔	◕	◕
assessment criteria and procedures, state-of-the-art (guide lines, recommendations and laws)	◔	◔	◔	○	◔	◕	◕	◔

availability of aids ○ ◔ ◕ ● (less → largely)

Fig. 7: Availability of aids for construction

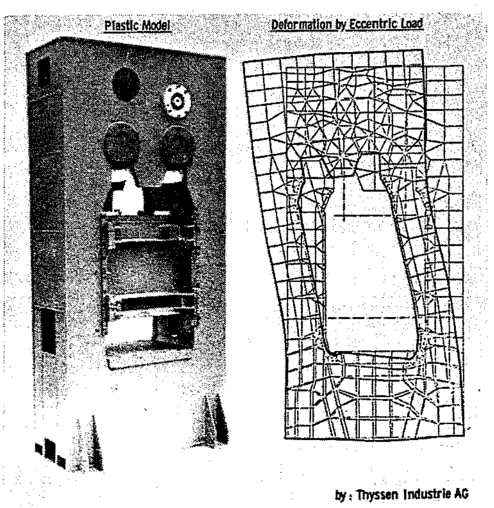
Depending on the kind and the extension of the problem nowadays, the designer can rely on desk calculators for common routine work or even request assistance from a computing centre.

The recently developed software enables him to conduct complicated calculation and evaluation procedures.

As a basis for comparing machines more and more measuring data is available according to the present level of technological development. It becomes more and more practical to collect all these data in handbooks for the designer. By means of relatively simple relations, the designer can refer these data to his particular problems.

As a typical example to show the applications of these means, a computation method for the static behaviour as well as a measuring procedure for the dynamic behaviour will be briefly explained.

A specimen for the application of software is the double crank press. Figure 8 shows how the influence of eccentric load on the distortion of the press frame can be calculated by the finite element method. Calculations for this model have been conducted in two as well as in three dimensions. The result of the calculation for a certain loading case can be seen on the left of the figure.



by: Thyssen Industrie AG

Fig. 8: Calculation of static deformation using finite element method

The topological model is built up of 2311 elements and contains 17 775 unknown. The computing time for 20 different crank shaft positions and loading conditions amounted to approximately 15 hours on an IBM 370/168. The preparation of data for the calculation involved approx. 75 man days. The trouble-shooting requires the same amount of time effort. Finally the interpretation of the results took again 75 man days.

Regarding the calculation of static behaviour of machine components or even complete machines, it can be stated that no major problems are encountered if the boundary conditions are known and if a sufficient computer capacity is available.

The application of the mean "calculation of the static behaviour" enables the designer to determine transfer functions in the simulation model of figure 6, e. g. the transferfactor c_R.

However, the calculation of the damping factor K_{FR} which is proportional to the velocity, is not practicable. Also the mathematical determination of the frictional transfer function K_F is quite uncertain.

Yet, both factors are necessary to describe the motion y_R of the frame.

Since the complex interaction between process, tool and machine cannot be analysed by the mean "computation method" one must still relay in this case on measuring procedures to achieve a sufficient accurate description of these interactions. The measuring procedure can be performed at simular existing forming machines and the result can be transfered to the actual design problem.

Furthermore, the determination by measuring the dynamic behaviour of complete machines is gaining importance. As an example for the means "analysis of the dynamic behaviour by measurement" a toggle drawing press will be treated in detail. For this purpose the "modal analysis" is used. By this method the vibrational behaviour can be visualized directly on a screen. The goals of such an investigation are the determination of the flexibility of the loaded components as well as the determination and evaluation of the vibrational modes corresponding to determined resonance frequencies. An additional advantage of the method is that the measuring devices can be used immediately at any machine because the equipment is fully transportable. Moreover, the results are available in short time. Figure 9 illustrates the procedure. First of all in the left hand part you see the structure of the press approximated by a topological model and stored in the memory of the Fourier-Analyzer. The model points relevant for defining the structure are marked on the frame. During the course of the measurement, the displacements of these points caused by a dynamic force between the ram and the bed of the press are recorded and stored. Also the magnitude of the exciting force is digitally stored in the memory of the analyzer.

The mathematical relation between exciting force and displacement $(\frac{X}{F})$ at each model point gives a transfer function that describes the dynamic behaviour between the point where the force is applied and the model point. With the aid of the computer many transfer functions will finally be analysed using the so-called "modal parameters" (figure middle). These quantities enable the mode shapes for each resonance frequency to be plotted.

Furthermore, it is very usefull that the designer is able to visualize the mode shapes on a monitor screen. Besides the plotted prints, the filming of the main mode shapes is recommended for documentation purposes. It is thus easier to imagine the dynamic machine displacement and picture the relative movements of the machine components to each other as in the case of plotted prints.

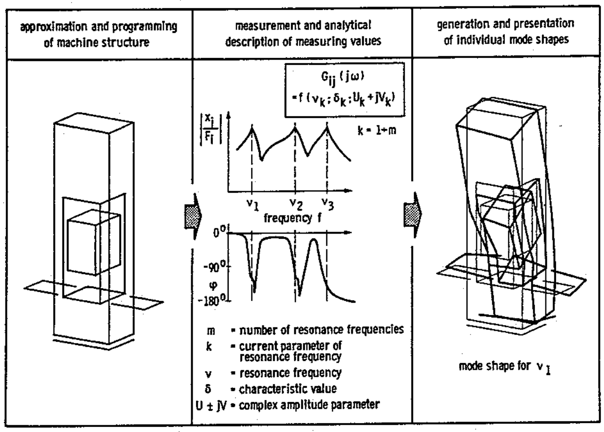


Fig. 9: Determining the vibratory form by modal analysis

The means brought up in figure 7, of which only two were more closely considered, enable a complete mathematical description of the transfer functions of the block diagram shown in figure 5. However, it must be remarked that although the simplified technical sequence of actions becomes more and more clear, the whole system remains so complex that it is necessary to confine the analysis to certain groups of interactions.

For instance, the vibrational and noise behaviour were completely neglected. Also the thermal behaviour of the equipment was not considered. The complexity of the system on the whole limits the analysis to subsystems. The extent of the subsystems being analysed depends strongly on the type of the forming operation studied.

A simulation of the interaction proves to be possible when the whole manufacturing system "forming" is simplified to the subsystem forming-process-machine. In order to determine the transfer functions characteristic for seperate blocks of the action sequence diagram it is necessary to apply the means available in the field of technology and machine evaluation.

Figure 10 shows a result of the simulation programm. It can be seen that there is a considerable interaction between the features of work material and the behaviour of the press. In the first simulation course, constant yield stress was presumed. The second course is done with strain hardening material while workpiece measurements and initial yield stress remain unchanged. The diagram shows the relationship between the technological quantity strain hardening and the mechanical quantity expressed by the punch displacement and punch speed.

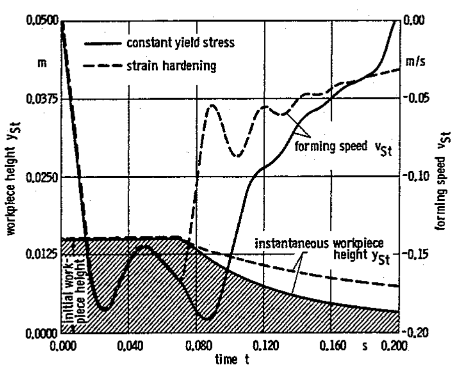


Fig. 10: Interaction between workmaterial properties and machine

4. Conclusion

An attempt is made to evaluate the complex interactions in forming processes. From case studies in the field of both,technology and machine design, interrelations are formulated in a qualitative manner and partly even quantitatively.

The means, which are necessary for the description of the interactions, are briefly discussed. Today an exact analysis of the whole manufacturing system process-machine-external factors is not possible because of lack of practicable means. Moreover, the demands of the subsystem external factors with respect to the forming process are not well defined. The development of means contributing to the description of the whole system forming will be our future assignment.

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