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USE OF CONVENTIONAL DYNAMOMETER CARDS IN THE ANALYSIS OF SUCKER-ROD PUMPED INSTALLATIONS

A conventional dynamometer (the most common type of measuring device in rod pumping well analysis) records polished rod loads versus rod displacement during the pumping cycle on a plot called dynamometer card. Calculations requiring rod loads and displacements as input variables must rely on information retrieved from these cards. There are many conditions that prevent the pumping analyst from getting the right type and the desired amount of reliable measurement data from dynamometer cards. These include: (a) the card's small physical size, (b) visual reading of the card can be insufficient, and (c) additional information not readily available from the card may also be needed.

The goal set forth in this paper is to present a novel technique for processing conventional dynamometer cards. The calculation method and the computer program developed for this purpose: (a) uses a simple computer configuration, (b) involves a simple, easy-to-learn procedure, (c) ensures the required accuracy, and (d) allows the retrieval of special information from the card that cannot be reached with other methods.

INTRODUCTION

Importance of Dynamometry

In analyzing the performance of a pumping system, the most valuable tool is the dynamometer which records the loads occurring in the rod string. These loads are measured either at the surface with a conventional polished rod dynamometer or at pump setting depth with a special downhole measuring device. In both cases, loads are recorded in the function of rod displacement or pumping time, during one or more pumping cycles, producing the familiar dynamometer "card". Since the variation of rod loads is a result of all the forces acting along the rod string, and since it reflects the operation of the pump as well as the surface pumping unit, an evaluation of the measured loads reveals valuable information on downhole and surface conditions. Accordingly, performance analyses of the downhole and surface equipment are usually conducted by running a dynamometer survey on the well.

The proper use of dynamometry techniques and the correct interpretation of the cards taken are of utmost importance for the production engineer when he tries to increase the profitability of sucker rod pumping. Proper interpretation of surface and downhole dynamometer cards reveals a wealth of information on the operation of the rod pumping system. The most important uses of dynamometer card analysis are the following:

- Determination of the loads occurring on the pumping unit structure and in the rod string.
- The torsional loading on the speed reducer and on the prime mover can be calculated.
- From the area of the card, the power required to drive the pumping unit can be found.
- After the counterbalance effect is found, the degree of the unit's counterbalancing can be determined.
- The condition and possible malfunctions of the sucker rod pump and its valves can be determined.
- Downhole problems can be detected making the analysis of dynamometer cards a powerful troubleshooting tool.

Use of Conventional Dynamometer Cards

The predominantly used conventional dynamometers, working on mechanical or hydraulic principles, record the loads at the polished rod as a function of polished rod displacement. Such "conventional" dynamometer cards are taken on a daily basis in all oil producing areas of the world and are the basic information available for pumping well analysis. The usual interpretation of such cards by visual means is a task for highly specialized analysts. Due to the many interactions of influencing parameters and the great number of possible pumping problems, an infinite number of dynamometer card shapes can exist, making the analysis of surface dynamometer cards more an art than an exact science. A proper analysis of these cards, therefore, heavily relies on the analyst's expertise and skill.

To ease the qualitative analysis of cards taken in the field the American Petroleum Institute published **API Bul 11L2** [1], where dynamometer cards for ideal pumping conditions (perfect fillage and no gas interference in the pump, pump in perfect mechanical conditions, etc.) are given. The published cards, obtained from an analog computer specifically built for the purpose, are classified according to the values of two dimensionless parameters: N/N_o' and $F_o/S/k_r$, also used in the **API RP 11L** [2] procedure. The use of **API Bul 11L2** involves the calculation of these dimensionless parameters and then the selection of the analog card closest to these conditions from the collection. If the shape of the measured card closely resembles the analog card just found, no apparent problems are present, otherwise further expert analysis is required.

If a quantitative analysis of dynamometer survey data is required and numerical values of the polished rod load have to be determined, most frequently the analyst must rely on visual reading of the dynamometer card. This approach works fine as long as the necessary number of polished rod loads is limited to a few values, e.g. when maximum and minimum loads, or pump valve test data are only needed. In such cases, visual reading of the card is easily accomplished and the required few load values are found with due consideration to the load scale of the dynamometer. However, when a more detailed analysis of the pumping system is required the retrieval from the card of a much greater number of polished rod load values is inevitable. The maximum number of points that can be obtained by manual reading is, of course, limited by the small physical size of the card and by the low accuracy of visual reading. Thus, manual evaluation of dynamometer cards cannot be successfully done if a detailed history of polished rod loads is required as an input to subsequent calculations.

In addition to the above considerations, one important fact must still be mentioned. The conventional dynamometer, in contrast to the more modern electronic types, records polished rod loads versus polished rod displacement. The conventional card, therefore, cannot be used to find the time histories of the polished rod load and the displacement. Nevertheless, knowledge of these functions is necessary if the calculation of downhole cards is desired through the solution of the damped wave equation written for the rod string.

As seen above, several conditions prevent the retrieval of the right type and the desired amount of information from dynamometer cards by the methods presently available. The data retrieval procedure introduced in this paper overcomes these problems and allows the determination of the right type and number of information from conventional dynamometer cards.

PREVIOUS DATA RETRIEVAL TECHNIQUES

The traditional analysis of dynamometer cards involves the visual reading off of a limited number of points from the card. This fairly time-consuming manual procedure can be accelerated with the use of special rulers with appropriate load scales or other simple devices. But its main drawbacks, the relative low accuracy and the poor reliability cannot be eliminated.

Basically, the same manual data retrieval technique is described in the appendices of **API Spec. 11E** [3], where a procedure is recommended for the calculation of torsional loads on pumping unit speed reducers. Although the recommended technique allows the determination of several points of the polished rod load vs. polished rod displacement function, the general accuracy of dynamometer card processing did not improve. Also, the number of points that can be read from the card is still limited.

The use of digitizers in processing dynamometer cards has become standard practice and has also increased the reliability of card analysis. **Gray** [4] reports on a simple procedure that can be used to read the coordinates of several points into a computer for further calculations. His digitizing procedure, however, does not permit finding of polished rod loads at equidistant crank angles, a very desirable feature when solving the damped wave equation. Since the most powerful application of dynamometer card data is the calculation of downhole cards through the solution of the wave equation, the method of Gray can find limited use in rod pumping analysis.

PROPOSED METHOD

Objectives

As shown above, most available data retrieval procedures for dynamometer card processing have limited accuracy and do not always provide the right type of information for well analysis. The aim of this paper is the introduction of a new technique for the evaluation of conventional dynamometer cards, which improves the accuracy and usefulness of the information received from such cards. The specific objectives set forth for the development of the proposed computerized model are:

- It should permit the determination of polished rod load and rod displacement values in a way allowing the utilization of such data in several different kinds of analysis of the pumping system.
- Both the number of points read, and the overall accuracy of the data retrieved from the card should be increased.
- It should use simple, readily available equipment.
- The procedure should be easy to use and to learn.

Theoretical Background

According to the objectives detailed above, one final result of the proposed data retrieval technique must be the polished rod load in the function of crank angle. Since the conventional dynamometer card is a record of polished rod load vs. polished rod displacement, an additional relationship is required to calculate the desired load - crank angle function. The polished rod displacement vs. crank angle function, based on an exact kinematic analysis of the pumping unit's motion and given in the **API Spec. 11E** [3] is ideally suited for this purpose and will be used in developing the calculation model. As stated in Spec. 11E, the non-dimensional form of the polished rod displacement is found from the basic formula:

$$\mathrm{PR}\,(\theta) = \frac{\psi_b - \psi}{\psi_b - \psi_t} \qquad (1)$$

where:

$\mathrm{PR}\,(\theta)$ dimensionless polished rod position (Position of Rods),

θ crank angle, and

ψ_b, ψ_t extreme values of angle ψ .

The definition of angle ψ for conventional pumping units is given in **Fig. 1**, showing the geometrical arrangement of the driving mechanism of those units. Angles ψ_b, ψ_t represent the two extreme values of this angle valid at the bottom and at the top of the polished rod's stroke.

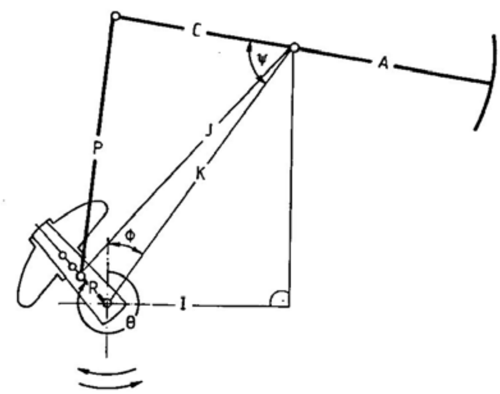

Fig. 1. Geometrical arrangement of a conventional pumping unit's driving mechanism

By utilizing the $\mathrm{PR}\,(\theta)$function the polished rod load vs. crank angle, values are obtained from the dynamometer card by using the following procedure, also given in API Spec. 11E:

- Begin with the crank angle θ, valid at the start of the upstroke.
- Calculate $\mathrm{PR}\,(\theta)$ and, based on its value, find the polished rod displacement.
- From the card, determine the polished rod load belonging to the displacement just calculated.
- Increase the crank angle by a constant increment and repeat the calculations until the full pumping cycle is covered.

The above procedure can only be used to find the load - crank angle function needed for calculating the torsional loading of pumping unit gear reducers. [5] For the other and probably more important use of dynamometer card data, i.e. the solution of the wave equation, however, rod loads and displacements are required in the function of time. Since these functions are not readily available from conventional dynamometer measurements, the use of special dynamometer arrangements is customary. The first special dynamometers recorded the displacement and load functions on strip charts for later evaluation but modern electronic models are directly hooked to a computer for on-line data acquisition. Such units are more expensive than ordinary dynamometers but, due to their many beneficial features, are gaining popularity.

When using a conventional dynamometer, the data required for the solution of the wave equation are implicitly contained in the card recorded by the surface dynamometer. The necessary displacement and load vs. time functions can only be determined if a constant angular velocity of the crank arm over the pumping cycle is assumed. In this case, the polished rod displacement vs. time function is found from a kinematic analysis of the given pumping unit, i.e. from **Eq. 1**. Using this relationship and reading the corresponding load and displacement pairs from the card, the points of the desired polished rod load vs. time function can be determined. [6] Application of this technique eliminates the need for expensive equipment and the data provided by the time-proven conventional dynamometer survey can readily be utilized for the analysis of downhole pumping problems. According to experiences gained by a major oil company on thousands of rod pumped wells, this approach gives practically identical results to those achieved when the more expensive electronic dynamometers are used, except when the pumping unit is driven by a fully loaded high slip motor. [7, 8]

As seen, one of the objectives of this paper can be met by the application of the theory detailed above which ensures that data retrieved from conventional cards can be used in different kinds of pumping analysis. The remaining objectives i.e. increasing the number and accuracy of the data received from the card, will be reached by the computerized technique presented in the following.

Details of the Calculation Procedure

Hardware Requirements

Basically, two methods are available for entering information from dynamometer cards into computers: either a digitizer tablet or a graphics plotter with digitizing capability can be used. The digitizer tablet, at least in the author's opinion, is not an ideal device for this purpose since its hand-held cursor moves in two directions on the tablet's surface, thus increasing the chances of input errors. An additional and much more serious disadvantage is that there is no direct way to ensure that points at a constant crank angle increment apart are digitized on the card.

Many graphics plotters possess digitizing capabilities and this feature can be very advantageously utilized for the special conditions of data retrieval from dynamometer cards. Since the movement of the plotter pen, or in our case the digitizing sight, can be controlled from a computer, the plotter can simultaneously be used for moving the sight on the card and for digitizing some selected points. This potential feature of graphics plotters was utilized by the author to develop the special digitizing program detailed in this paper.

The hardware needed for the above program consists of:

- A personal computer,
- A Hewlett-Packard 7470A or 7475A Graphics Plotter, and
- A Hewlett-Packard Digitizing Sight (HP Part No. 09872-60066) installed in the penholder of the plotter.

Preliminary Operations

In order to increase the accuracy of data retrieval, the original dynamometer card is enlarged and the enlarged copy is used for digitizing. Since the load and displacement axes of the card are not necessarily parallel to the physical coordinate axes of the plotter, the transposition and/or rotation of the card relative to the plotter coordinate system must be established. As shown in **Fig. 2**, a minimum of four points have to be digitized to find the parameters of coordinate transformation, i.e. the angle of rotation α and the transposition of the axes, X_0 and Y_0.

These preliminary operations form the basis of transforming the points read in the plotter coordinate system into the coordinate system of the card, i.e. finding the corresponding load and displacement values. Given the plotter coordinates X and Y of one point on the card, the transposed coordinates X' and Y' are calculated as:

$$X' = X - X_0, \tag{2}$$

$$Y' = Y - Y_0. \tag{3}$$

Now the X' - Y' coordinates must be rotated to find the coordinates in the card's system:

$$S = X' \cos\alpha + Y' \sin\alpha, \tag{4}$$

$$F = Y' \cos\alpha - X' \sin\alpha. \tag{5}$$

Since all the above coordinates are in length units, the polished rod load and displacement values are calculated by applying the force and displacement scales of the card axes found before:

$$Load = F \; F_{scale}; \tag{6}$$

$$PR = S / S_{max} \tag{7}$$

Automated Digitizing Process

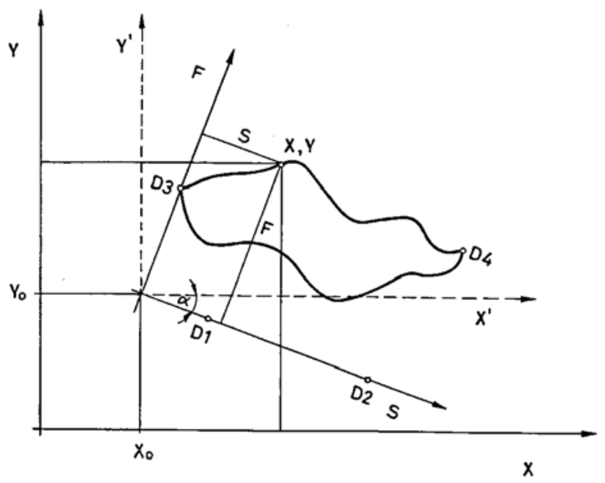

Fig. 2. Dynamometer card and plotter coordinate systems

The main objective of the digitizing process is to retrieve from the dynamometer card the polished rod load values that belong to different crank angles. In order to meet simultaneously the data input requirements for the solution of the damped wave equation as well, these angles must be taken at a constant crank angle increment apart. To accomplish this task, the graphics plotter's special capabilities are utilized in the computer program by forcing the digitizing sight to travel along a selected SR = const. line. As the sight passes over the dynamometer card, the user immediately signals to the computer that reads the actual plotter coordinates and calculates the load valid at the given crank angle. The sight then moves to a new SR = const. line belonging to the next crank angle and the next load is determined with the same procedure. This process is repeated until a complete pumping cycle is covered, i.e. until the whole card is digitized.

Before digitizing, the desired number of points to be retrieved from the card is specified that determines the value of the crank angle increment that must be used.

Then, an ascending series of crank angles is set up, beginning with the angle valid at the start of the upstroke and covering the full pumping cycle. The crank angles at the start of the upstroke and the downstroke vary with the geometry of the pumping unit, the relevant formulae are given in **Table 1**. The dimensionless polished rod positions that belong to each value of the crank angle series are calculated and stored in computer memory based on **Eq. 1**.

Table 1. Crank angles at the start of the upstroke and the downstroke

Unit Geometry	Θ_u	Θ_d
Conventional or Torqmaster	$\phi - \varepsilon_1$	$\phi + \pi - \varepsilon_4$
Mark II	$\phi + \pi - \varepsilon_2$	$\phi - \varepsilon_3$
Air Balanced	$\phi - \pi + \varepsilon_2$	$\phi + \varepsilon_3$

The definitions of angles ε_i:

$\varepsilon_1 = \sin^{-1}\dfrac{C\sin\psi_b}{P+R}$	$\varepsilon_2 = \sin^{-1}\dfrac{C\sin\psi_b}{P-R}$
$\varepsilon_3 = \sin^{-1}\dfrac{C\sin\psi_t}{P+R}$	$\varepsilon_4 = \sin^{-1}\dfrac{C\sin\psi_t}{P-R}$

After these data preparations, the actual digitizing of the dynamometer card follows. Since the card has two loads for any polished rod position, one on the upstroke, and one on the downstroke, the actual case must always be determined by comparing the actual crank angle to the crank angles at the polished rod's extreme positions (see **Table 1**). The digitizing procedure is illustrated on the flowchart given in **Fig. 3**, valid for any crank angle on the upstroke portion of the dynamometer card.

At the start of the procedure, the polished rod position in card units, S is calculated based on the precalculated PR value valid at the actual crank angle. Now a sufficiently large polished rod load, LStart is assumed and its card coordinate, F is found. After the plotter coordinates X and Y, corresponding to these card coordinates are determined, the digitizing sight is moved to this position in a "pen down" state. The computer then gives an audible signal and the user visually checks whether the sight is still above the dynamometer card's upper portion. If so, no user signal is given and the assumed polished rod load is decreased by Dload1. Another pair of plotter coordinates is calculated and the digitizing sight is moved to the new point and the above process repeats. Thus the sight travels along a PR = const. line towards the upper portion of the dynamometer card while its current state (either "pen up" or "pen down") is continuously monitored by the computer program. As soon as the user detects that the sight has just crossed the upper part of the card, he/she signals to the computer by pressing the "pen up" button on the plotter's front panel.

Now the digitizing sight's direction of movement is reversed and at the same time the magnitude of its movement in each step is substantially reduced by using a load step, Dload2 much less than the previous Dload1. The above detailed process is used but the sight, in the "pen down" state, now approaches the upstroke part of the card from below. By using an appropriate load increment, Dload2, it can be ensured that during its upward travel the sight once will lie exactly over one point of the upper portion of the dynamometer card. At this moment, the user signals to the computer by pressing the "pen up" button on the plotter, and the load, F, valid at the actual crank angle is found.

The above procedure is repeated for the remaining crank angle values until the end of the upstroke is detected. Then the downstroke portion of the card is digitized using a slightly modified version of the procedure just described. The only difference is that now the digitizing sight starts its movement from below the downstroke portion of the card.

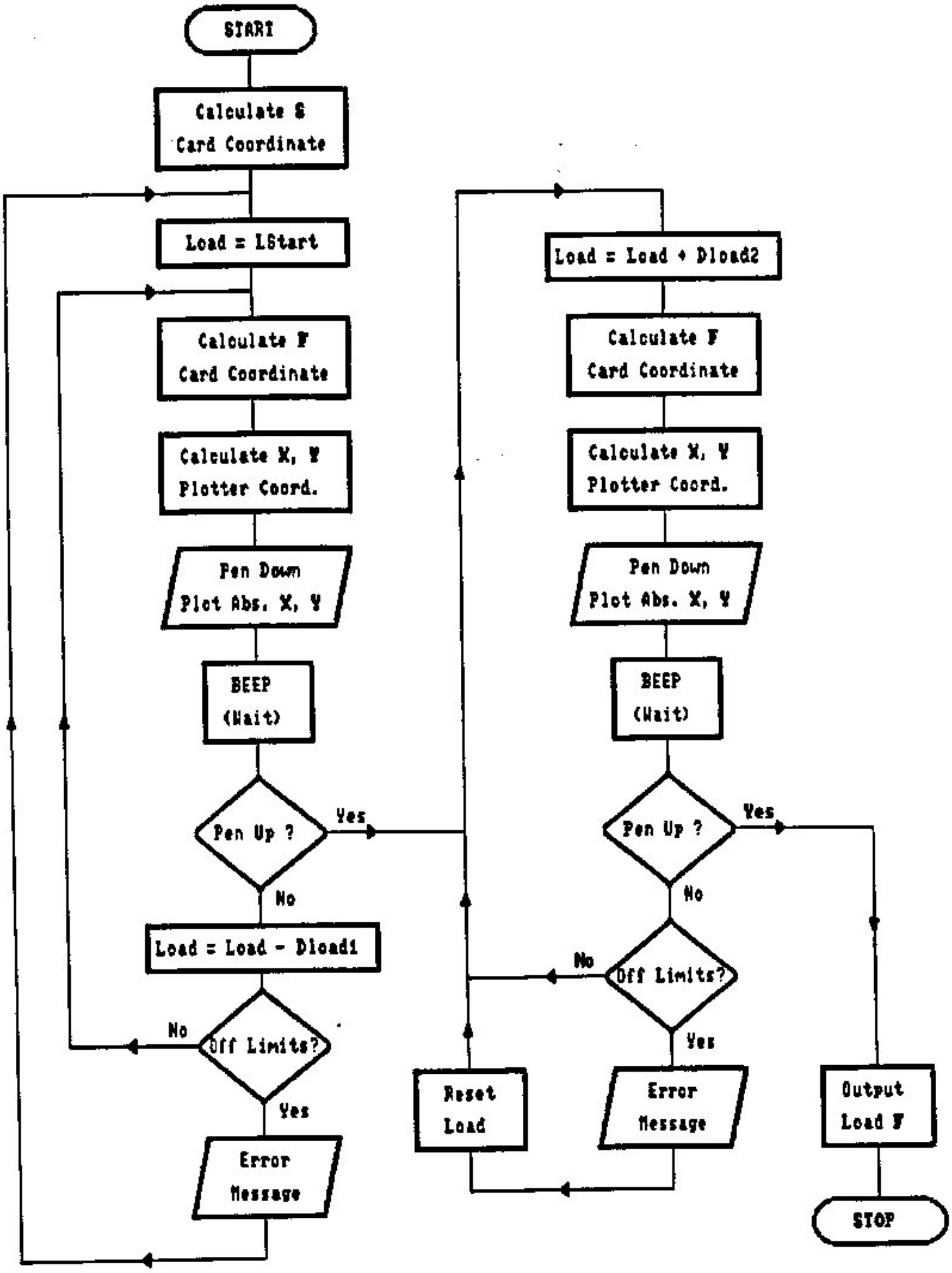

Fig. 3. Flowchart of the automated process
for digitizing the upstroke portion of the dynamometer card

SAMPLE APPLICATION

In the following, an example problem is presented with the use of the computer program **CARDIGIT** [9]. This program not only enables one to retrieve the necessary load and displacement data from the card but it is also stores in a data file all relevant data for use in a number of different analyses to be performed later

An important field of application for dynamometer card data is the downhole analysis involving the calculation of pump cards. Such analyses require polished rod load and displacement data in the function of time. As discussed before, the program **CARDIGIT** satisfies this requirement and stores the digitized data at equidistant crank angle values and thus provides the necessary input data for downhole card calculations. Calculation of downhole and pump cards is based on a variety of different theories, the solution presented in **Fig. 4** utilizes the analytical method of Gibbs, performed by the program **ANAWAVE**. The figure displays the dynamometer card with the calculated downhole cards and clearly shows a nearly perfect condition at the pump.

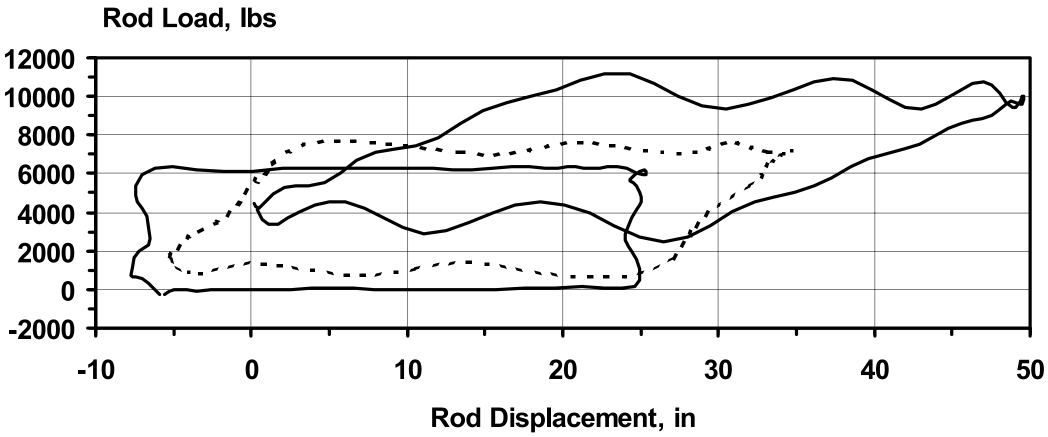

Fig. 4. Calculated downhole cards output from program **ANAWAVE**

CONCLUSIONS

The technique described in the paper can greatly improve the accuracy and usefulness of the information retrieved from conventional dynamometer cards. The following main benefits are available to the rod-pumping analyst:

- The total number of the points read and the overall accuracy of the data received from the card are increased as compared to previous methods.
- The results of the digitizing process can readily be utilized in different analyses of the pumping system, the most important one being the determination of downhole cards.
- The digitizing process is simple and requires little effort from the user as compared to previous methods.
- Simple, universally available equipment is used.

REFERENCES

1. Catalog of Analog Computer Dynamometer Cards. API Bul 11L2, 1st Ed., American Petroleum Institute, Dallas Texas, December 1969
2. Recommended Practice for Design Calculations for Sucker Rod Pumping Systems (Conventional Units). API RP 11L 4th Ed. American Petroleum Institute, Washington D.C. 1988
3. Specification for Pumping Units. API Spec. 11E, 15th Ed., American Petroleum Institute, Washington D.C. 1988
4. Gray, C. R.: Dynamometer Analysis Using a Digitizer and an IBM PC. Paper SPE 15288 presented at the Symposium on Petroleum Application of Microcomputers of the SPE in Silver Creek, Colorado, June 18-20, 1986
5. Takács, G.: Torque Analysis of Pumping Units Using Dynamometer Cards. Proc. 36th Annual Southwestern Petroleum Short Course, Lubbock Texas, 1989 p. 366-76
6. Takács, G. - Papp, I.: Dynamometer Card Analysis Using Minicomputers. (in Hungarian) Köolaj és Földgáz, March 1978, p. 65-73
7. Ford, W. H. - Svinos, J. G.: Effective Application of Beam Pumping Diagnostics. Paper SPE 17444 presented at the SPE California Regional Meeting, Long Beach, California, March 23-25, 1988
8. Svinos, J. G.: Successful Application of Microcomputers to Analyze Sucker Rod Pumps. Paper SPE 17789 presented at the SPE Symposium on Petroleum Industry Applications of Microcomputers, San Jose, California, June 27-29, 1988
9. Takács, G.: MODERN SUCKER-ROD PUMPING. PennWell Books, Tulsa Oklahoma, 1993