Statistics & Control, Inc.

White Paper

OptiRamp® Rod Pump Diagnostics

Maximizing Oil Extraction Performance with Advanced Control Technology

Hasballah Ahba
Ivan Susanto
Nibukat Zaradan
Desy Kurniawan
Lawrence Youngblood
Vadim Shapiro
Dmitriy Khots, Ph.D.

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Introduction

Most of the world's 85 million barrels of crude oil per day are extracted using rod pump systems, also known as sucker rod pumps or pumpjacks. A large oil field may have tens of thousands of individual rod pumps often located in difficult-to-access sites, each requiring timely maintenance to ensure optimal operation. The maintenance logistics costs are substantial enough for companies to invest into rod pump control and diagnostics systems. Statistics & Control, Inc., (S&C) has developed a rod pump diagnostics solution for oil field managers as part of its *OptiRamp*® suite of advanced control tools.

The *OptiRamp* Rod Pump Diagnostics Module provides oil field operators with smart alerts and maintenance scheduling decisions by analyzing well performance, automatically generating and classifying pump dynamometer cards to determine anomalies (leaking valves, gas interference, etc.), and performing trend analysis to predict the next required maintenance. The *OptiRamp* Rod Pump Diagnostics Module visualizes individual well and rod pump system performance through the integrated Web visualization studio. This white paper describes the rod pump system structure, how the dynamometer cards are generated and classified as normal vs. abnormal (along with type of abnormality), and the *OptiRamp* solution and software architecture necessary to perform the required analytics.

The *OptiRamp* Rod Pump Diagnostics Module provides the following benefits to oil field operators:

1. Maintain maximum production.
2. Save energy by optimizing the pumping unit operation.
3. Minimize down time by predicting potential pumping problems.
4. Detect and identify abnormal situations early to prevent further damage to pumping system equipment.
5. Optimize manpower utilization from maintenance recommendations and improved scheduling.

Rod Pump System

A rod pump system is a relatively simple mechanism used to extract subsoil fluids. It is inexpensive to operate and typically lasts for a long time, given proper maintenance. Figure 1 shows the general schematic of the above-surface structure of a basic rod pump system.

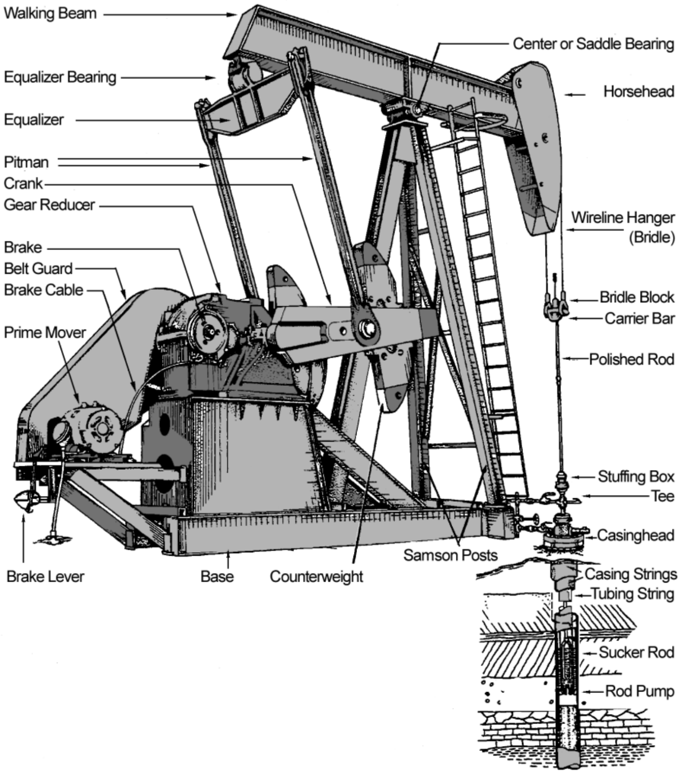

Figure 1. Sucker rod pump architecture; source: http://petrowiki.org/

The five major components of the rod pump system are:

- Prime mover—typically an electrical motor, though in some cases where the well is remote and has no electricity, prime movers may be used as an internal combustion engine.
- Gear reducer or gearbox—ensures optimal and, more importantly, sustainable pumping speeds.

- Pumping unit—transforms the circular motor motion into a vertical reciprocating movement.
- Sucker rod string—a “chain” of sucker rods (of length between 6 and 22 feet) connected by rod couplings that transmits the mechanical energy received from gearbox to the subsurface pump.
- Subsurface pump—critical component of the entire system that allows the fluids to be elevated from the reservoir to the surface.

A typical positive displacement subsurface pump consists of the working barrel, a plunger, a traveling valve (part of the plunger), and standing valve (part of the working barrel). Though there are two major pump types—tubing and rod—this paper will focus on the latter kind. Figure 2 shows a closer look at the rod pump in both downstroke and upstroke conditions.

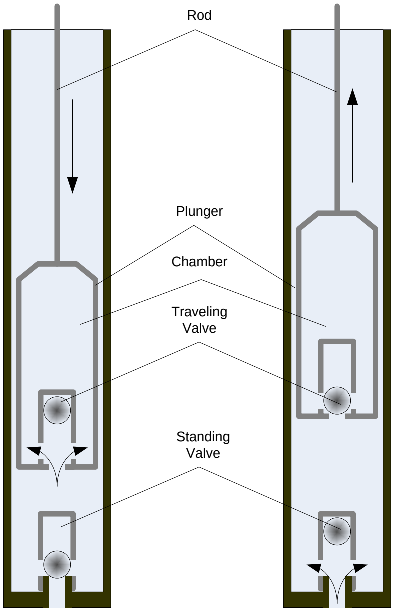

Figure 2. Rod pump architecture

In the downstroke (shown on the left of Figure 2), the traveling valve opens and the standing valve shuts. The fluid column weight is supported by the subset of the standing valve and is transmitted to the tubing though the barrel. The plunger’s volume is flooded by the fluid. Plunging the sucker rod string causes a small fluid production at the surface due to the volume that was shifted.

In the upstroke (shown on the right of Figure 2), the traveling valve shuts and the standing valve opens. The fluid shifted by the plunger arrives at the surface, while the barrel is refilled through the standing valve. In this way, the weight of the fluid in the tubing is transmitted to the sucker rod string.

The subsurface pump and its diagnostics mechanism is the primary object of this white paper. Since the pump is located near the producing zone, often thousands of feet deep in the well, there is no clear way to understand its behavior. Thus, it can only be inferred from plotting various pump parameters on a diagram called the dynamometer card.

Additionally, one of the major operating problems in a rod pumping system is matching inflow into a well with a pumping system that has a fixed productivity. Since inflow constantly changes due to reservoir qualities, the displacement of the installed pumping system never exactly matches the ability of the well to produce fluid. Therefore, the well is usually either under- or over-delivering. The *OptiRamp* Rod Pump Diagnostics Module provides the following methods to match capacities:

1. Regulatory control of engine speed when pump speed is automatically adjusted based on the varying inflow rate.
2. Pump off control shuts the unit down for short periods of time, allowing the fluid to build up inflow.

OptiRamp Solution

The *OptiRamp* Rod Pump Diagnostics and Web Analytics Modules provide a high level of analytical support for operational decisions and process management. *OptiRamp* helps reduce operating costs and increase production by providing operators with information necessary for performance analysis, problem diagnosis, and equipment optimization. The *OptiRamp* system, which can operate either as a stand-alone device or as part of a centralized optimization system, consists of software modules installed on a central server that obtains data via SCADA. The system can produce individual well performance reports that show the dynamometer cards transferred from the individual controllers to the central server for further analysis. A complete surface and downhole equipment analysis is conducted by the *OptiRamp* Rod Pump Diagnostics Module to detect possible issues. In addition, control actions can be initiated from the central server via SCADA. Figure 3 shows a possible scenario of the data flow between the pumps and the main controller.

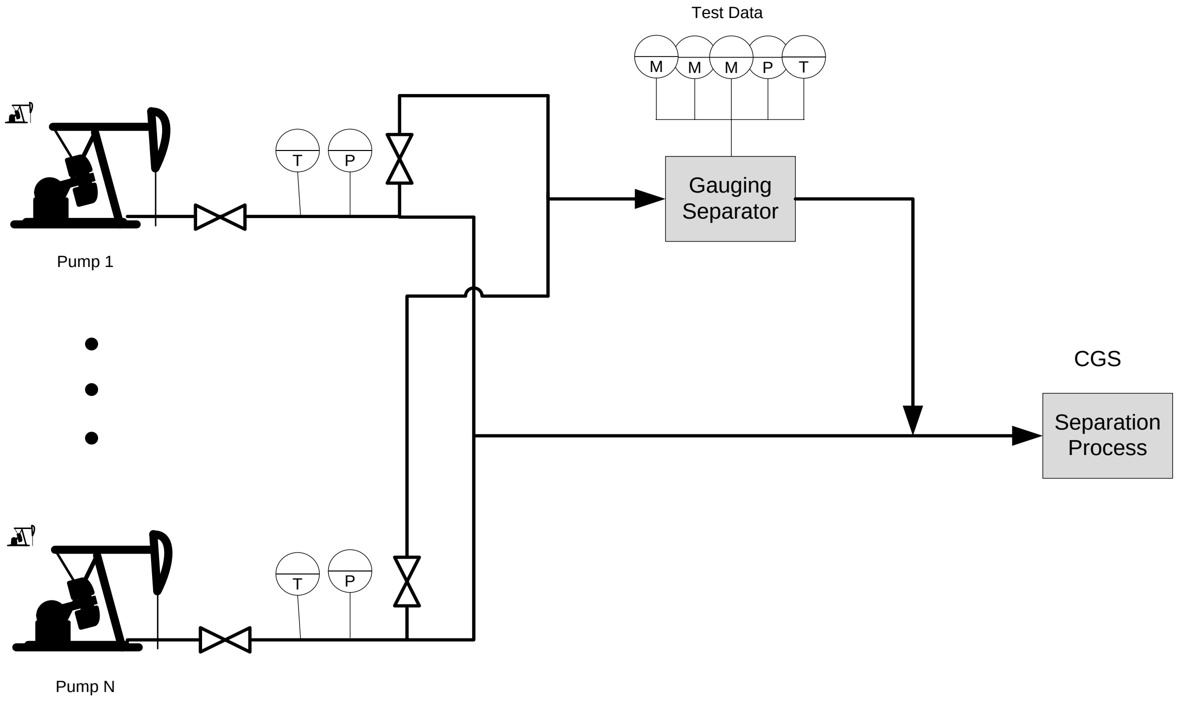

Figure 3. Data flow scenario

The *OptiRamp* Rod Pump Diagnostics Module requires the following dynamic data (meaning measured over parametrically defined time scans) to be captured by the existing pump control system:

Pwh	Wellhead Pressure
ρ	Fluid Density (based on well test records)
N	Speed
L	Rod Position
U	Voltage
I	Motor Current
T	Torque

Module Software Architecture

Figure 4 displays the *OptiRamp* Rod Pump Diagnostics Module architecture.

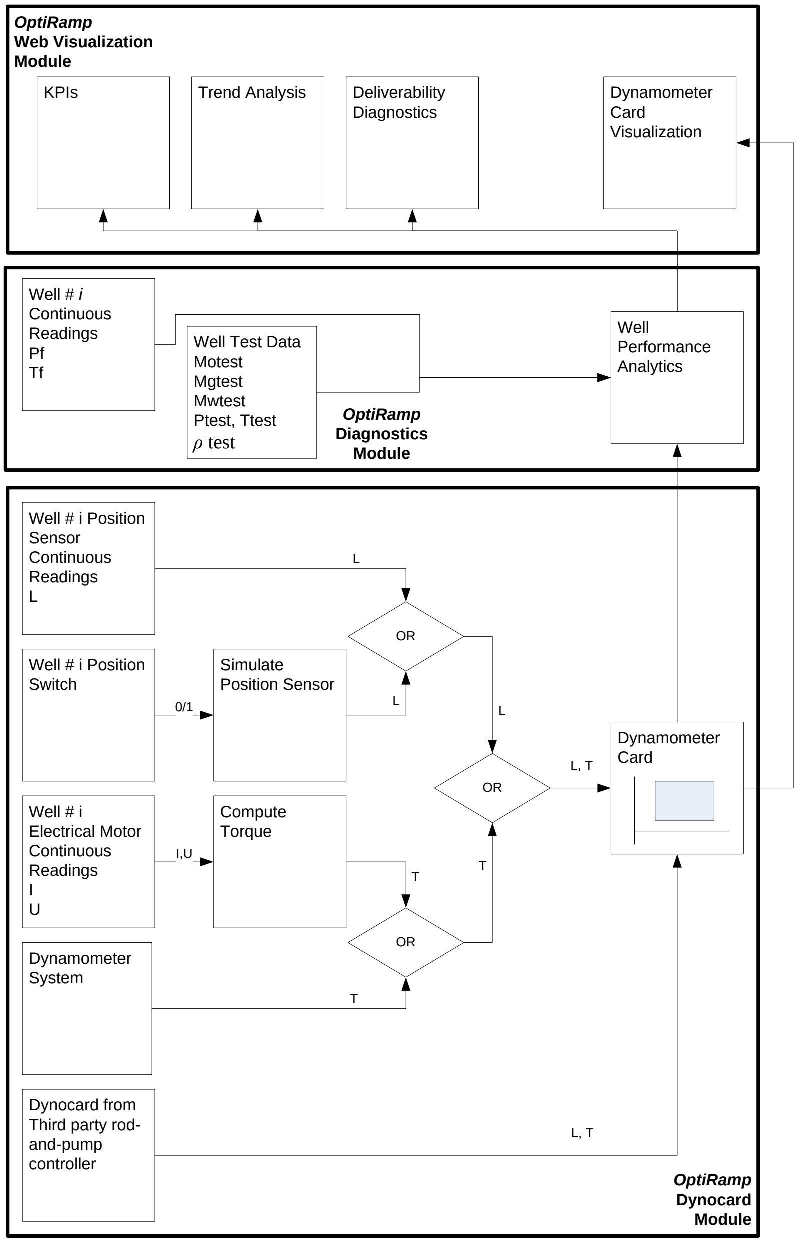

Figure 4. *OptiRamp* rod pump diagnostics module architecture

The *OptiRamp* Rod Pump Diagnostics Module performs the following functions:

1. Gather rod displacement
    - Read continuous position sensor
    - Simulated position from a position switch
2. Gather rod load
    - Dynamometer system
    - Computed based on current, voltage readings, and electrical motor specification
3. Gather real-time pressure and temperature readings from field sensors

4. Plot the resulting dynamometer card (via the Web Visualization Module, discussed in detail later in this white paper)
5. Obtain the dynamometer card from a third-party controller
6. Display the dynamometer card locally or remotely (via the Web Visualization Module)
7. Store real-time and historical dynamometer card data
8. Read well test records
9. Well performance analysis (discussed in detail later in this white paper)
10. Continuous performance monitoring
11. Trend analysis to detect pump degradation (discussed in detail later in this white paper)
12. Maintenance recommendations
13. Notify about declining productivity (via the Web Visualization Module)
14. Alarm about abnormal situations
    - High torque limit notification alarms about high torque conditions, which may cause damage
    - Low torque limit notification indicates a problem with the motor/pump unit
15. Regulatory control of engine speed
16. Pump off control

Well Performance Analysis

The rod pumping system's useful work is done by the downhole pump. This work is calculated as an increase of potential energy of the liquid pumped. The electrical motor provides the required power, *Pe*. This power can be computed based on measured voltage (*U*) and current (*I*) and covers all pumping system requirements, including useful work and all power losses. Power losses include friction losses (*Pf*), hydraulic losses (*Ph*), and wellhead pressure losses (*Pw*).

The *OptiRamp* Rod Pump Diagnostics Module transforms the following equations into an optimization problem that minimizes the discrepancies by finding the optimal individual power values:

1. *Energy balance*—the sum of power losses and useful power are equal to the consumed electrical motor power for the upstroke.
2. *Energy balance*—the sum of power losses and useful power are equal to the consumed electrical motor power for the downstroke.
3. *Dynamometer card pattern*—to be discussed in more detail in the next section.

At a high level, power balance reconciliation is based on least squares optimization. Let Δ_{X_i}, Δ_{Y_j}, and Δ_{Z_p} denote the target errors in $X_i(t)$ (consumed electrical motor power), $Y_j(t)$ (power losses), and $Z_p(t)$ (useful power), respectively. For a steady-state process, the optimization problem is set up as follows: minimize equation (1).

$$\sum_{i,j,p}\left[\left(X_i(t)+\Delta_{X_i}\right)-\left(\left(Y_j(t)+\Delta_{Y_j}\right)+\left(Z_p(t)+\Delta_{Z_p}\right)\right)\right]^2, \qquad (1)$$

subject to constraints $\left|\Delta_{X_i}\right| \le \delta_{X_i}$, $\left|\Delta_{Y_j}\right| \le \delta_{Y_j}$, and $\left|\Delta_{Z_p}\right| \le \delta_{Z_p}$, where δs are the signal tolerances. For a transition-state process, the optimization problem is given with similar constraints, but the objective function is given by equation (2).

$$\sum_{i,j,p}\left[\left(X_i(t)+\Delta_{X_i}\right)-\left(\left(Y_j\left(t+\tau_j\right)+\Delta_{Y_j}\right)+\left(Z_p(t)+\Delta_{Z_p}\right)\right)\right]^2 \qquad (2)$$

The optimization problem solution is a set of estimated power values for the selected time period. These methods are described in more detail in the *Material Balance Reconciliation Module White Paper* available on the S&C website.

Dynamometer Card

Background

The main diagnostics tool for a rod pump system is the dynamometer card, which is a graphical representation of the relationship between rod load and stroke position. There are two types of dynamometer cards: surface and pump (or downhole). Surface dynamometer cards have been in use for over 80 years. They represent plots of measured rod loads at the various stroke positions, where the load is typically measured in pounds of force and the position (or rod displacement) is measured in inches. An example of a surface dynamometer card is shown in Figure 5.

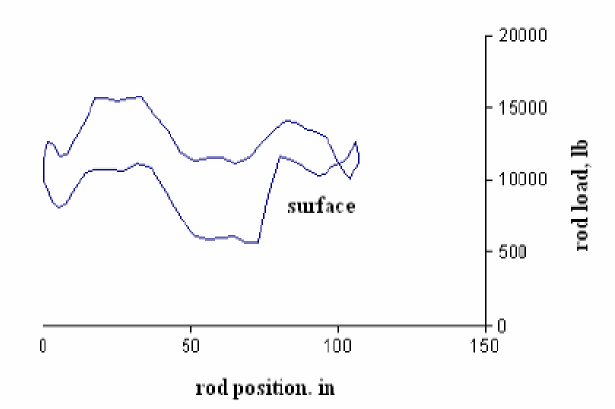

Figure 5. Surface dynamometer card example; source: S. G. Gibbs

The shape of the surface dynamometer card is affected by changing downhole conditions. Traditionally, these conditions are determined from the card by visual interpretation of an experienced analyst. This method has been proven ineffective in multiple conditions; hence, a better assessment of what truly reflects downhole conditions was needed. Thus, the downhole dynamometer card was invented. The only way to truly measure downhole dynamometer cards is to pull the sucker rods and the pump itself out of the well, which is cost prohibitive given large deployments. A method introduced by S. G. Gibbs used differential equations to calculate the card values. Therefore, the downhole dynamometer card can be defined as a plot of the *calculated* loads at various rod displacement positions of the pump stroke; the downhole card represents the load that the pump applies to the bottom of the rod string. The downhole dynamometer card load is generally negative. Using S. G. Gibbs' equations, an example of a downhole dynamometer card corresponding to the surface dynamometer card in Figure 5 is displayed in Figure 6.

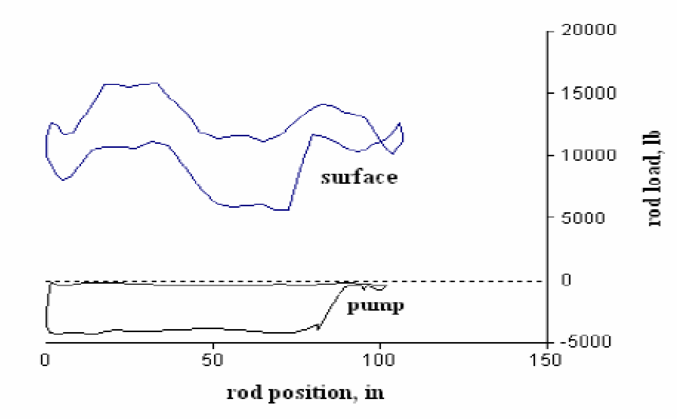

Figure 6. Downhole dynamometer card example; source: S. G. Gibbs

Equation (3) shows S. G. Gibbs' historical wave equation that describes the elastic behavior of a sucker rod.

$$\frac{\partial u^2(x,t)}{\partial t^2} = v^2 \frac{\partial u^2(x,t)}{\partial x^2} - c\frac{\partial u(x,t)}{\partial t} + g \quad , \tag{3}$$

where *u(x,t)* is the solution for rod position at time *t*. For details and definitions, see *Rod Pumping—Modern Methods of Design, Diagnosis and Surveillance*, by S G. Gibbs. S&C engineers have solved the following two challenges using S. G. Gibbs' equation for pump diagnostic purposes. First, it is imperative to find the numerical solution to the equation so that the system is able to plot the downhole dynamometer card. This equation is solved using finite difference methods, where the second partial derivative is expressed according to equation (4).

$$\frac{\partial u^2(x)}{\partial x^2} \approx \frac{\partial}{\partial x}\left[\frac{u\left(x+\frac{\Delta x}{2}\right) - u\left(x-\frac{\Delta x}{2}\right)}{\Delta x}\right] \approx \frac{u(x+\Delta x) - 2u(x) + u(x-\Delta x)}{\Delta x^2} \tag{4}$$

Given an established "grid," a set of points at which the unknown partial differential equation is sampled, and applying equation (2) at each grid point leads to a system of differential equations that can be solved for the unknown sample values either explicitly (where values are updated on the grid one point at a time) or implicitly (through a system of linear equations).

Second, once the solution is found and the card plotted, pattern matching is performed to classify the downhole dynamometer card into normal or abnormal downhole conditions.

Downhole Dynamometer Card Classification

Various downhole dynamometer card shapes have already been classified into normal (full pump) vs. abnormal conditions (e.g., leaky valves or gas interference). Figure 7 illustrates a sampling of such shapes.

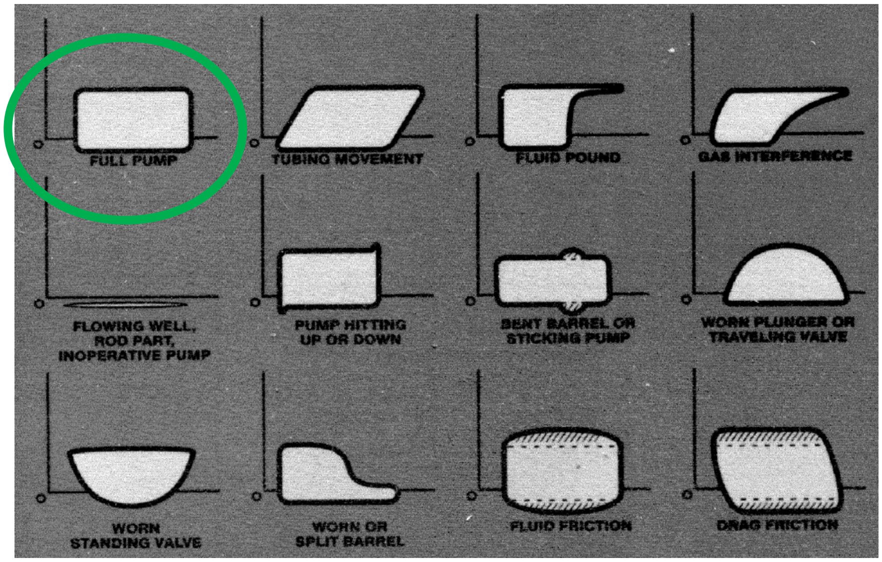

Figure 7. Downhole dynamometer card classification; source: S. G. Gibbs

As with the surface dynamometer cards, each downhole card is typically investigated by an experienced analyst in order to determine the appropriate classification. However, latest developments in pattern recognition technology allow for a much more financially advantageous estimate that replaces an otherwise costly manual process, especially for larger oil fields. Using an automatic system to recognize downhole dynamometer card patterns helps anticipate the problems with earlier identification and, therefore, helps take both corrective and prevention measures for it.

S&C has developed the following technology that helps to automatically classify each calculated downhole dynamometer card into one of the predetermined classes. The goal is to perform multilevel classification by treating each downhole dynamometer card as an observation. S&C algorithms are customized, in that they use data from each individual well across the entire oil field rather than prebuilt histories, to generate training and validation datasets. S&C engineers also work closely with Chevron specialists to use any available feedback from operators and analysts on what the predetermined classes may look like for the current oil field conditions. The algorithms retrain themselves after misclassified cases are identified to ensure maximum classification accuracy.

The classification problem is viewed as a four step process. First, downhole dynamometer cards are represented (coded) as an N-dimensional vector in the feature space. Second, the algorithm selects the type of classification algorithm to be used—supervised vs. unsupervised. In supervised learning, the members of the training and validation datasets are classified by a human (thus historical records of well cards for a particular oil field are critical to acquire prior to training). In unsupervised learning, no such classification is required. Third, in case of supervised learning, classification algorithms use the training dataset to learn and build the classifiers, which is followed by comparing results with the validation dataset to ensure that the misclassification rate remains low and stays similar to the training dataset. In case of unsupervised learning, resulting classifiers are matched to existing labels. Fourth, new unknown cases are classified according to parametrically defined decision criteria.

Specifically, the feature space representation of the downhole dynamometer cards occurs as follows. Let $U_i^j = \{\boldsymbol{x}_{i1}^j, \dots, \boldsymbol{x}_{ip}^j\} \in \mathbf{R}^2$ be the set of p two-dimensional points that represent a sampling of coordinates of the upstroke curve (U_i^j) measured for well $i = 1, \dots, n$ calculated over a time frame $j = 1, \dots, m$. Let $D_i^j = \{\boldsymbol{y}_{i1}^j, \dots, \boldsymbol{y}_{ip}^j\} \in \mathbf{R}^2$ be a similar set corresponding to the coordinates of the downstroke curve. Typically, p =100, i.e., 100 points representing each card direction are sufficient for statistically significant analysis. Still, this forms a formidable calculation problem (regardless of the chosen classifier) as this is equivalent to 400 variables to be mined for patterns.

In the case of supervised learning, a new set of n-dimensional vectors is formed, $U_i^j = \{U_i^j, D_i^j, y_i^j\}$, where y_i^j is the manually identified label for each historical downhole dynamometer card. The *OptiRamp* Rod Pump Diagnostics Module is integrated with the *OptiRamp* Modeling Module and has access to all available predictive modeling routines. In particular, the following supervised multilevel classifiers are frequently used in downhole dynamometer card classification: artificial neural networks (ANN) and ordinal logistic regression.

The ANN algorithm implemented in the *OptiRamp* Modeling Module is the Multilayer Perceptron (MLP). The MLP network consists of individual neurons. Each artificial neuron receives n weighted inputs that are summarized and transferred to the neuron output. Figure 8 displays the structure of the individual neuron with three inputs.

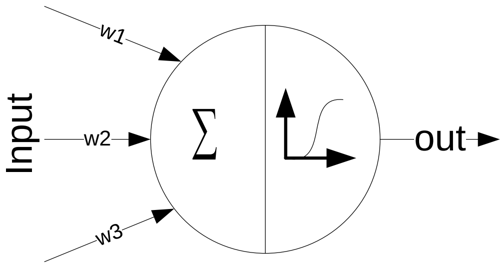

Figure 8. Artificial neuron with three inputs

The composition of the combination and transfer function constitute the activation function. The MLP model uses the hyperbolic tangent as the activation function. The MLP weights are initially chosen at random and then adjusted such that the error function (5) is minimized on the training set:

$$E = \frac{1}{n+m} \sum_{l=1}^{n+m} (y_l - F(U_l, D_l)) \quad , \tag{5}$$

where $F(U_l, D_l)$ is the MLP output for each potential label. The output is essentially the probability of each case to belong to a particular label.

Ordinal logistic regression is used to predict categorical targets with more than two values. The word ordinal also means that there is an inherent order in the labels. For downhole dynamometer cards, the ordering can be performed according to the risk (or cost) of each abnormal classification. Let *C* be the total number of various *ordered* downhole dynamometer card labels. Equation (6) defines the cumulative odds θ_q for each index $q = 1,\ldots,C$.

$$\theta_q = \frac{P(label\ of\ order \leq q)}{P(label\ of\ order > q)} \ , \tag{6}$$

where *P(label of order ≤ q)* is the probability of each downhole dynamometer card belonging to a label less than or equal to *q*. The ordinal logistic regression then uses maximum likelihood estimation to find the coefficients *β* for the logit function (7):

$$\ln(??_q) = P(??, U, D) \ , \tag{7}$$

where $P(??, U, D)$ is an r^{th}-degree polynomial with *4p* independent variables.

Given the high dimensionality of the feature space, the *OptiRamp* Rod Pump Diagnostics Module has embedded certain feature extraction algorithms, such as the Principal Component Analysis (PCA). In short, PCA transforms the original vectors into noncollinear—orthonormal—vectors, each of which is a linear combination of all of the variables of the original feature space. It is also worthwhile to note that as more classifications become available from analysts, the algorithm needs to be retrained to ensure the highest classification accuracy by minimizing the misclassification rate given by equation (8).

$$Misclassification\ Rate = Type\ I\ Error\ Rate + Type\ II\ Error\ Rate \tag{8}$$

The unsupervised classifier implemented in the *OptiRamp* Rod Pump Diagnostics Module is k-means clustering. Setting $k = C$, the algorithm takes the downhole dynamometer card vectors $x_{ij} = \{U_i^j, D_i^j\}$ and groups them into *k* “lookalikes” such that equation (9) is minimized.

$$\underset{S}{\mathbf{argmin}} \sum_{l=1}^{k} \sum_{x_{ij} \in S_l} \left\| x_{ij} - \mu_l \right\|^2 \quad , \tag{9}$$

where $S = \{S_1, \ldots, S_k\}$ is a possible solution and $??_l$ is the centroid of the points in S_l. The members of the resulting set *S* are then matched to the downhole dynamometer card labels to describe each S_l. The algorithm will then be able to classify a new downhole dynamometer card into its corresponding cluster S_l, which is consequently assigned a label, i.e., classified.

Trend Analysis

Trend analysis is a procedure used to analyze performance parameter decline rates and to forecast future performance. A curve fit of past parameter performance is done using standard curves based on the well-known Arps equations. This curve fit is then extrapolated to predict potential future performance.

Arps equations represent the relationship between an efficiency metric, such as a well production rate, and time. Let *PV(t)* be the efficiency metric (could be a measured process variable or a calculated value) at time *t*. The relationship between the efficiency metric and time is defined according to equation (10).

$$PV(t) = \frac{PV_0}{(1+bDt)^{1/b}}, \tag{10}$$

where PV_0 is the initial efficiency metric value, $b \in [0,1]$ is a constant whose values determine the type of decline, and *D* is the decline rate. For example, when $b = 0$, the decline is called Exponential and is visualized by Figure 9.

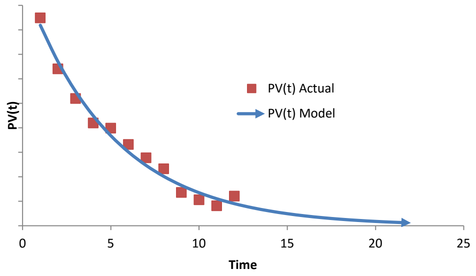

Figure 9. Process variable with exponential decline

Please contact S&C sales support to receive more information about the Trend Analysis algorithms; full descriptions are available in the *OptiRamp* Knowledge Base.

Web Visualization

The *OptiRamp* Rod Pump Diagnostics Module is integrated with a Web Analytics (WA) interface that creates a visual representation of Key Performance Indicators (KPIs) using Meter WA objects. The goal of the WA platform is to provide operators with a real-time view of each pump's technical state. WA also uses Six Sigma techniques to display deviations of each KPI from their healthy (or normal) conditions and alarms if the deviation exceeds computed or user-specified thresholds. Various colors are provided to accomplish proper action based on the alarms. If the color is not green, maintenance is required. Also, service work performed on the pump will move the indicator back to the "green" (healthy) zone. "Green" color of all KPIs is the acceptable technical state of each monitored unit. The goal of the *OptiRamp* Rod Pump Diagnostics Module is to help operators maintain all equipment KPIs in the “green” zone. Also, the WA tool displays both dynamometer cards locally and remotely.

Ultimately, the Web visualization studio allows oil field operators to maintain pump efficiency at a high level and to perform maintenance for the monitored units at the right times.

About Statistics & Control, Inc.

S&C—an engineering consulting and technology company headquartered in West Des Moines, IA—solves complex challenges for customers through its unique technology and its highly seasoned team of professionals. The company has a global portfolio spanning the energy, oil and gas, utility, and digital oil field industry sectors. S&C provides clients with turbomachinery control solutions that easily integrate with the existing system as well as *OptiRamp*® solutions, which focus on process and power analytics to optimize processes and, in turn, reduce costs and increase reliability. S&C also provides consulting, dynamic system studies, modeling, automation, training and OTS, and support services.

Statistics & Control, Inc.
4401 Westown Pkwy, Suite 124
West Des Moines, IA 50266 USA
Phone: 1.515.267.8700
Fax: 1.515.267.8701