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Optimization in Oil and Gas Pipeline Engineering

A survey of applications of optimization techniques in oil and gas pipeline engineering is presented. These applications include the optimal design, optimal expansion, optimal control and optimal operation of pipeline systems. Applications in offshore pipeline engineering is also involved.

Introduction

Mathematical programming has been used in the oil and gas industry for many years. It developed rapidly in the last decade because of the oil crisis, the availability of cheaper and faster computers and the existence of more efficient optimization algorithms. Among the extensive and diverse applications in the oil industry, the optimization of oil and gas pipeline engineering problems is a very active area.

Several surveys concerning the applications of optimization in oil and gas industry have been published and are available in the literature. Dougherty (1972) made a comprehensive review on the optimization of various oil field problems. Durrer and Slater (1977) surveyed the optimization of oil and gas production. Lasdon and Waren (1980) made a general survey of nonlinear programming applications, in which the application in oil and gas industry is discussed. However, none of these surveys paid particular attention to the optimization of oil and gas pipeline systems.

The purpose of this paper is to focus on the optimization of oil and gas pipeline engineering problems. This includes the optimal design, optimal expansion, optimal operation and optimal control of pipeline systems. Applications in offshore pipeline engineering are also cited since they represent some of the most promising topics which will be receiving attention in the years to come.

Optimal Design of Pipeline Systems

In the optimal design of a gas pipeline system, the objective is often to determine the following variables in an effort to minimize total cost:

- number of compressor stations;
- location of compressor stations, i.e., lengths of pipeline segments between compressor stations;
- diameters of the pipeline segments; and
- suction and discharge pressure at each compressor station.

In this class of problems, the objective function is nonlinear. Normally there are equally constraints for length and flow requirements and inequality constraints for pressure and compression ratios. Some of these constraints are nonlinear.

The efforts to optimize this problem or its components (that is, to determine some of the aforementioned design variables mentioned) began in the 1960's. One of the investigations is undertaken by Hax (1967) who used Kunh-Tucker conditions to determine the optimal operating conditions of the system. The application of this method, however, is very limited. Wong and Larson (1972) used dynamic programming to optimize the suction and discharge pressure for a unbranched gas pipeline with fixed segment lengths and diameters of a specific number of compressor stations. But, compared to the results for the same example given by Edgar, et al. (1978), the results of Wong and Larson's were incorrect because they did not satisfy the constraints. Martch and McCall (1972) also used dynamic programming to optimize the pressures in a pipe network, but the number and the locations of compressor stations and the diameters of pipeline segments were predetermined. This is because the so-called "curse of dimensionality" of dynamic programming (i.e., the number of operations will grow exponentially as a function of the number of variables).

The work of Rothfarb, et al. (1970) seemed to be a conspicuous development on this topic at that time. Due to the development of a merge technique to eliminate those uneconomical diameter combinations and networks without enumeration, the possible diameter assignments grew in an approximately linear fashion instead of exponentially as a function of the number of nodes. Thus, the technique provided an efficient tool for optimizing gas pipeline network by dynamic programming. A heuristic program was also introduced for helping in the optimization of the configuration of the network. Nevertheless, no compression facilities were optimized in this study, and junctions other than those at existing wells are not possible. Zadeh (1973) suggested some improvements to Rothfarb's method by using either a minimum cost flow approach or a combination of dynamic programming and sorting to solve the same problem.

Another notable development was made by Flanigan in 1971 who used a constrained steepest descent method to

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optimize pipeline diameters and compressor sizes simultaneously subject to certain nonlinear constraints. The variables were divided into decision and state variables, and ratios of Jacobians were calculated in every step to take into account the interaction between the state and decision variables specified by the constraints. However, the number and the sites of compression stations were not optimized in this study and the inequality constraints were not considered.

Bhaskaran, et al. (1979) studied the optimal design of a gas gathering pipeline network. The design of such a system can be distinguished as the configuration, the junction location and the diameter assignment problem. The last problem was solved by a linear programming approach to minimize the total cost of the network and select the diameters of each link for a given network configuration. But the positions of compressor stations are not considered in this model.

Cheeseman (1971a, b) reported the application of a pipeline design optimization software. A univariate search technique was used for determining the minimum cost. Although the univariate search method is not a very efficient algorithm for nonlinear constrained problems, a 70-percent reduction in design-optimization time and a 30-percent reduction in design cost with an improved design were obtained.

From the previous review it can be seen that the optimization of pipeline systems as a nonlinear constrained problem and with a large size requires more efficient algorithms.

Considerable developments in nonlinear programming has taken place in the last decade. New algorithms continually appear such as the generalized reduced gradient method, augmented Lagrangian method and sequential quadratic programming algorithm, (Waren and Lasdon, 1979; Sandgren and Ragsdell, 1980).

Edgar, et al. (1978) utilized the generalized reduced gradient algorithm in the optimization of gas pipeline system design. This more efficient and powerful algorithm made it possible for the first time to optimize all the aforementioned design variables simultaneously. The algorithm was used directly in instances where the capital costs of the compressors were a function of horsepower output but have zero initial fixed cost. When the capital costs are comprised of a nonzero initial fixed cost plus some function of horsepower output, it was necessary to use a branch-and-bound scheme with the GRG algorithm.

Efforts have been made for optimizing the design of large size gas pipeline system in recent years. Soliman and Murtagh (1982) developed an algorithm which could optimize the number of compressor stations, pressure ratios and diameters for a predetermined tree structure pipeline configuration. A large-scale optimization code MINOS developed by Martagh and Saunders (1978) was used. This code utilizes sparse matrix methods to deal with large number of variables and achieves a superlinear rate of consequence by using quasi-Newton approximations to the second-order terms in the objective function. However, this code could only handle those nonlinear problems with only linear constraints and give the optimized diameters in "continuous" form. In a recent paper by Murtagh and Soliman (1983), a subgradient optimization procedure was used to solve for the discrete pipe sizes after the optimal continuous solution was obtained by MINOS. The method was posed for the design of relief-header systems of oil-refineries, but it also could be used for gas distribution networks and gas gathering systems. An application of this algorithm to a pipeline system with up to 205 pipe sections, each involving 50 discrete pipe sizes, was reported.

It would be interesting to find how much benefit could be gained from optimization of a pipeline system. Wyman (1978) reported that by using geometric programming to solve a water conveyance pipeline system in Algeria, a conservatively estimated savings of $50 million in project costs is expected [19]. The method was developed by Wilde and McNeill (1979), which also could be used for the design of crude oil pipeline.

Optimal Expansion of Pipeline Systems

There is another type of design optimization problems in pipeline engineering, that is, the optimal expansion of an existing pipeline network. Martch and McCall (1972) and Rothfarb, et al. (1970) studied this topic in their papers. In general, the capacity expansion planning of a pipeline system involves the determination of the future expansion times (timing decision), sizes (sizing decision) and locations (location decision). Olorunniwo (1981) developed a mathematical model which could be solved to obtain the optimal value of these decisions. However, this model is too complex for practical application. A hierarchical approach was used to obtain an approximately optimal solution. Olorunniwo and Jensen (1982a) used a decomposition approach to change this complex multifacility capacity expansion problem into a series of much simpler single facility problem, and the possible timing of capacity expansion for each facility could be determined. Using these results in Olorunniwo, et al. (1982b), the same authors applied a two-level hierarchical solution technique to determine the optimal number, locations and sizes of the facilities that are required in the network over the given planning horizon. A code LSGRG developed by Lasdon and Waren (1977) and capable of solving large-scale nonlinear problems with nonlinear constraints was used, in which the generalized reduced gradient method is applied.

Optimal Operations of Pipeline Systems

Millions of dollars were spent every year in fuel cost for operating the compressors and pumps in pipeline systems. It has become imperative to optimize fuel usage at the compression and pumping stations. Gopal (1980) suggested a method to optimize the operations of pipeline pumping stations. The objective is to bring on-line a combination of only those pumps which will pump the desired volume for minimum fuel cost, based on their individual fuel rates. Balas additive integer programming algorithm was used to select the optimal pump combination, hence only a few combination evaluations were needed. In addition, dynamic programming was used to optimize the discharge pressure of the station. Singh (1981) suggested some alternative ways to solve this problem.

Optimal Control of Pipeline Systems

The optimization of aforementioned pipeline operations was based on the fixed fuel cost of each machine, no control function was involved. However, the fuel consumption rate of pumping or compression machine is a function of their speed and load, which in turn can be adjusted while operating. In this sense, a simple decision-making procedure is not sufficient. Accordingly, efforts have been made to introduce optimal control theory into the optimization of pipeline station operations. Osiadacz (1980) developed a method for optimal control of a gas compression station equipped with motor-compressors. The goal of the optimization in this study is to minimize the cost of energy consumed by the compressors. However, the fuel consumption rate of each engine was expressed mathematically as the function of speed. For a given set of gas flow, suction pressure and discharge pressure, which was assumed optimal for the pipeline investigated, the algorithm determined the number of machines necessary in the compression station, feasible combinations of machines and the speeds over the set of feasible points. The penalty function method was used to obtain the optimal solution while the total energy cost was minimized. Osiadacz and Bell (1981), altered this algorithm to a local optimization procedure for a gas compression station. Measured values of suction and discharge pressure together with flow through the compression station were used to optimize the parameters for the station. In addition, a control and adjustment level was added to ensure proper operating conditions for the compressors and thereby to reduce the cost of maintenance and repairs. This was done by keeping the actual compression ratios and power outputs of the machines in operation within reasonable limits. The algorithm could be implemented on a digital computer. Some experimental investigations showed that an average decrease of approximately 20 percent in the unitary fuel consumption was obtained.

Optimization of Offshore Pipeline Engineering

Offshore oil and gas operations require great outlays of capital, in which the cost of installing underwater pipelines is a significant factor. Proper design and construction of these systems are of extraordinary importance and efficient optimization techniques could be very helpful.

Rothfarb, et al. (1970) investigated three aspects of the optimal design of offshore gas pipeline system. He studied the selection of pipe diameters in a specified pipeline network to minimize the sum of investment and operation costs, the design of minimum-cost network structures with given gasfield locations and flow requirements and the optimal expansion of an existing pipeline network to include newly discovered gas fields. The method they used was discussed in the previous section of this paper.

In offshore pipeline installations, a critical factor is the design of the pipe-laying operations. The most severe stress levels are usually experienced in this phase and they must be kept within suitable safety limits in order to guarantee the integrity of the sea-line. Maier, et al. (1980) developed a method to optimize the stinger geometry for deep sea pipelaying. The procedure is to select the parameters governing the geometry of adjustable pipe-supporting system in laying barges, in order to minimize either bending moment peaks or the thrust supplied by the tensioners. The variable metric algorithm and linear programming approach were used separately for these two types of problems.

A submarine pipeline is usually laid so that it rests on the sea bottom freely. Since the sea bed profile is usually irregularly hilly, costly trench excavations are needed to avoid excessive bending moments in the pipe and to bury it for protection. Thus the problem arises for determining profile changes of minimum cost under the condition that an assigned curvature be nowhere exceeded. Giannessi, et al. (1979) developed a method to optimize the excavation profile for a pipeline freely resting on the sea floor. The optimal design problem is considered with reference to a discrete model of the mechanical system, as the minimization of a linear cost function under linear constraints and a single, nonlinear constraint. This nonlinear problem was reduced to a sequence of linear programming problems. However, the cost per unit length of a trench excavation is much better represented by a quadratic function of the depth, particularly in soft ground. Therefore, in the reference, the same authors (1982) formulate the problem as the minimization of a convex quadratic cost function under linear constraints and a nonlinear complementarity constraint. Then the problem is solved by reducing it to a sequence of convex quadratic programming problems leading to the optimal design situation. The method was believed to provide a first basis for practical solution of this optimization problem in structural and geotechnical engineering.

Conclusions

A survey of the use of optimization techniques in oil and gas pipeline engineering is presented. It shows that wide spectrum of subjects have been investigated in the last decade. Newly developed mathematical programming algorithms have been unceasingly utilized in this field to improve the optimization efficiency. Significant benefit could be obtained from the use of optimization techniques in the design of pipeline systems.

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