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Optimization of an Optical Fiber Drawing Process under Uncertainty

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Optical fibers are used in diverse applications ranging from ocean and terrestrial cables to remote sensors and to light guides in medical applications. The information and telecommunications industries are other fields where optical fibers are actively used. However, the full potential of optical fibers has not been realized because of performance and production limitations. In the manufacturing process, high draw speeds result in large temperature gradients, which often lead to inferior quality fiber with poor optical and mechanical properties. On the other hand, low draw speeds lead to superior quality fiber with better optical and mechanical properties. Here, quality is achieved at the expense of a reduced rate of production. Therefore, the realization of good quality fiber without unduly compromising the production throughput can be assessed through the solution of an optimization model. The objective is to maximize the fiber draw speed subject to constraints on fiber mechanical and transmission properties. Additional complications arise in the optimization problem when uncertainties in process and model parameters are accounted for.

1. Introduction

Optical fibers are used in a considerable number of applications ranging from ocean and terrestrial cables to remote sensors and to light guides in medical and other applications. They have also found wide usage in the information and communications industry. Because of the increased demand on bandwidth for transmitting large volumes of information faster, cheaper, and more reliably, manufacturing high-quality optical fibers that will guarantee reliability in performance at high production levels deserves much attention. In the manufacturing process, high fiber draw rates often result in inferior quality fiber with poor mechanical properties. On the other hand, low draw speeds lead to superior quality fiber with better mechanical properties at the expense of decreased rate of production. The realization of good quality fiber without unduly compromising the production throughput is accomplished through the solution of an optimization model. Naturally, since there are significant uncertainties in process and model parameters, there is a need to account for them in the optimization model.

Accounting for uncertainty in chemical process design has been an area of active research in the past few years. Most engineering processes and designs are based on models having parameters which take on nominal values. However, in real time, processes fluctuations abound. These variabilities arise because of varying process conditions (e.g., temperature instabilities) and inaccuracies in the experimental determination of model parameters (e.g., energy of activation, diffusion constants, and viscosity parameters). Hence, for a process to remain feasible (all process constraints are satisfied) at the operation stage, it is imperative that the effects of uncertainties are accounted for at the design stage. Infeasibilities during the operational stage lead to suboptimal and poor quality products. There are some instances where safety is a major concern. For instance, Rooney and Biegler[1] have shown that failure to consider uncertainty in the design of a flexible pressure relief valve could lead to a large pressure increase and possible explosion. A vast majority of the work done in the area of design under uncertainty has focused on systems where the cost function and constraints are analytic in nature.[1−10] However, uncertainty considerations in processes where the cost function and constraints are nonanalytic has received very little attention. The optical fiber fabrication process falls under this category. These processes are governed by a highly nonlinear system of partial differential-algebraic equations (DAE). Given inputs to the DAE model, outputs of interest are generated and used in computing the objective function and constraints needed in the optimization problem.

The objective is to maximize the fiber draw speed subject to constraints on fiber mechanical (e.g., defects, residual stress, and drawing tension) and transmission (e.g., refractive index profile) properties while simultaneously taking into account uncertainties in process and model parameters. Because of the nonlinearities inherent in the fiber drawing model, the objective function and constraints also turn out to be nonlinear. The fiber drawing optimization problem is thus formulated as a nonlinear programming (NLP) problem. The split-and-bound (SB)[11] method for solving the two-stage optimization problem (TSOP) under uncertainty has been adapted for the fiber drawing problem. The SB method uses sequential quadratic programming (SQP), which is a local optimizer, for solving the various NLP subproblems. In view of this, optimization runs are carried out using multiple initial guesses of the decision variables in order to guarantee a near-global optimal solution.

This paper systematically studies (1) the effect of uncertainty on fiber draw speed and (2) the effect of constraints on fiber draw speed. The production throughput, which is related to the fiber draw velocity, will be used as a measure of the process performance. The study of the effect of uncertainty on fiber draw speed therefore gives much insight into what represents an acceptable compromise on the fiber draw speed in the presence of uncertainties. Finally, the study of the effect of constraints on the fiber draw speed is necessary, since this provides information as to what is an acceptable deviation from

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