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STABILIZER DESIGN FOR INDUSTRIAL CO-GENERATION SYSTEMS [1]

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Abstract: Existing large industrial control systems often exhibit poor tracking and disturbance rejection capabilities due to a large number of decentralized control loops. To improve these, a stabilizer design procedure is proposed based on H_∞ optimization. The procedure is simple to apply and requires only some of the closed-loop transfer functions. Application of the approach in the Syncrude utility plant shows that it can indeed improve the disturbance rejection performance and the stabilizer designed is easy to implement and test in practice.

Keywords: Stabilizer design, H_∞ optimization, co-generation systems, boiler control, industrial applications.

1. INTRODUCTION

Co-generation systems are frequently used worldwide to generate electric and mechanical power in industrial facilities. The Syncrude Canada Ltd (SCL) integrated energy facility located in Mildred Lake, Alberta, is a typical example of this class of systems. In brief, this utility plant consists of a boiler system, a header system and an electricity generating system. The boiler system consists of three utility boilers, three CO-type boilers and two once-through steam generators (OTSG). The header system includes headers at four different pressure levels (900, 600, 150 and 50 psi, 1psi $\approx$ 0.1451MPa). The 900# header receives steam from the boiler system and then distributes the steam for three different usages: (i) to other process to extract bitumen from oil sands, (ii) to numerous turbines to generate electricity, (iii) to three other headers to generate steam at different pressures. The overall plant, like many similar ones available worldwide, is thus a rather complex, nonlinear, interconnected system.

The boiler system is responsible for the steam production, whose *quantity* (measured by its flow rate) and *quality* (measured by its pressure and temperature) play a crucial role in the plant operation. All the generated steam is accumulated in the 900# header. For the plant to operate properly, the steam pressure of the 900# header should be maintained within tight bounds. Feedback control is thus used to ensure that the boilers generate enough steam and simultaneously maintain the steam pressure and the steam temperature of the 900# header to their respective setpoints. Due to the physical characteristics of the different boilers, in the present control system, the utility boilers are responsible for the steam pressure, the CO-type boilers for the steam flow rate, and the OTSG's for the steam temperature.

From a control system's point of view, co-generation systems such as the one described above present a challenge. Clearly, this plant is a large, interconnected, and fairly nonlinear system. For a variety of reasons, the standard practice is to approach control design by dividing the task into hundreds of single-input single-

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output loops, and then design (decentralized) compensators, mostly of the proportional-integral type. The Mildred Lake plant is not an exception to this rule. Indeed, the plant has been in operation for almost thirty years and since its creation it has been controlled by a large number of decentralized PI loops, mostly tuned on line by well trained operators. Currently the plant shows poor response to steam load changes. Two causes contributing to these problems are nonlinearities and coupling. Nonlinearities constitute an obvious problem in any design. In the present case, on-line tuning of PI controllers assumes small variations with respect to operating conditions, thus overlooking the nonlinearities altogether. In this plant, however, provisions have been taken to compensate for the nonlinear effects. The plant contains several smaller subsystems which can provide additional steam or other forms of relief, if the 900# pressure in the main header exceeds or is below certain limits. Roughly speaking, coupling effects are perhaps a more serious problem. Coupling effects originate from overlooking the multivariable nature of the plant.

To improve the system response, two methods can be considered:

(1) Re-design the control system using multivariable techniques which take explicit account of the effects of coupling.
(2) Design a "stabilizer", namely, a secondary controller which "supervises" the action of the local controllers, and provides relief whenever necessary.

The first solution is probably the most desirable one, at least from a control system designer's point of view. See, for example, (Pellegrinetti and Bentsman, 1994; Zhao *et al.*, 1999; Tan *et al.*, 1999) for multivariable controller design in power systems. Multivariable controllers, however, are difficult to implement in a plant with the present characteristics, and would require a major investment to replace the present control structure. Moreover, plant operators, well trained in tuning PI loops and simple control modifications, are reluctant to incorporate multivariable techniques which are virtually impossible to re-tune on line. The second solution is simpler in that it does not require changing the structure of the control system currently in operation and is simple to implement. Here we use the term "stabilizer" because the situation we discuss here is similar to the well-known power system stabilizers (PSS) introduced by Anderson and Fouad (1977) and often used in the power industry.

The paper is organized as follows. In Section 2 we give a general discussion of the stabilizer design and propose several design strategies based on H_∞ optimization. In Section 3 we apply our proposed method to the Syncrude Mildred Lake plant and describe the stabilizer design process in detail. Section 4 presents the simulation results for the stabilizer designed in Section 3. Finally, in Section 5 we offer some concluding remarks.

As mentioned, the plant is nonlinear and rather complex. Care must be thus taken to simulate the results under realistic conditions. In the present case, Syncrude has available a simulation package, known as SYNSIM (Rink *et al.*, 1996). While the package is extremely valuable as an analysis tool, it is unfortunately not suitable for control design given the high degree of complexity used in its model. Indeed, care was taken during the development of this package to incorporate minuscule details and secondary effects, not typically incorporated in a control oriented model. The result is a very high order model which contains approximately 500 state variables and thus impossible to use in control design, yet invaluable as a simulation tool. This package has been extensively used by Syncrude's personnel and true plant measurements are very closely resembled by the predictions obtained with the model. The final controller will be simulated and compared to the existing design under what can be assumed to be fairly realistic conditions.

2. STABILIZER CONFIGURATION AND DESIGN

Consider the stabilizer configuration shown in Figure 1, where the symbols are defined as follows:

P_0:	process model	P_d:	disturbance model
C_0:	original controller	C_s:	stabilizer
r:	reference signal	d:	process disturbance
y:	process output	u:	process input
u_0:	controller output	u_s:	stabilizer output

Our goal is to improve tracking and disturbance rejection performance of the closed-loop system. We will approach this goal by adding another feedback loop from some of the most important variables to be regulated to the process inputs.

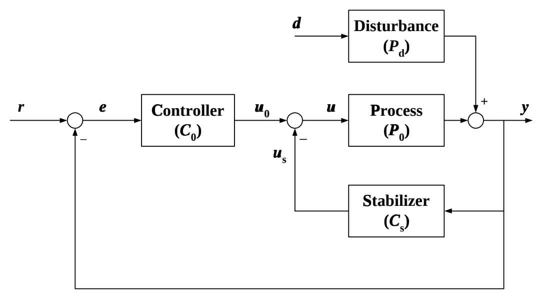


Fig. 1. Stabilizer configuration I

From Figure 1, we have

$$u = u_0 - u_s = C_0 r - (C_0 + C_s) y \quad (1)$$

$$y = P_0 C_0 r - P_0 (C_0 + C_s) y + P_d d \quad (2)$$

Thus

$$y = (I + P_{us} C_s)^{-1} (P_{rs} r + P_{ds} d) \quad (3)$$

where

$$\begin{aligned} P_{us} &:= (I+P_0C_0)^{-1}P_0 \\ P_{rs} &:= (I+P_0C_0)^{-1}P_0C_0 \\ P_{ds} &:= (I+P_0C_0)^{-1}P_d \end{aligned} \tag{4}$$

The output of the stabilizer is then

$$u_s = C_s(I+P_{us}C_s)^{-1}(P_{rs}r+P_{ds}d) \tag{5}$$

To cast the stabilizer design in the H_∞ framework, we proceed as follows:

(1) To improve the tracking performance of the existing system, we solve the following H_∞ problem:

$$\inf_{C_s} \left\| \begin{array}{c} W_1(I+P_{us}C_s)^{-1}P_{rs} \\ W_2C_s(I+P_{us}C_s)^{-1}P_{rs} \end{array} \right\|_\infty \tag{6}$$

where W_1 and W_2 are weighting functions on tracking and extra control effort.

(2) To improve disturbance rejection, we solve the following problem:

$$\inf_{C_s} \left\| \begin{array}{c} W_3(I+P_{us}C_s)^{-1}P_{ds} \\ W_4C_s(I+P_{us}C_s)^{-1}P_{ds} \end{array} \right\|_\infty \tag{7}$$

where W_3 and W_4 are weighting functions on disturbance rejection and extra control effort.

Note that P_{us}, P_{rs}, and P_{ds} are *closed-loop* transfer functions from u, r, and d to y, respectively, when the stabilizer loop in Figure 1 is open. So in the stabilizer design we do not need open-loop models. This is an important observation since, as explained in the next section, the model used in the design will be obtained via closed-loop measurements using system identification techniques. While open-loop models are very difficult to obtain using closed-loop measurements, our approach is not affected by this issue. This is particularly important in the present case since the open-loop plant *is not* asymptotically stable and thus open-loop measurements would be very difficult to obtain.

In the discussion above, we assume that all process variables are used to design the stabilizer. This is neither convenient nor practical, since (i) in terms of the plant performance, some output variables are important, and some are less important; (ii) some variables are already effectively controlled by existing controllers. Thus in the stabilizer design we will focus on those important variables which are not effectively controlled by the existing controllers.

In the sequel we will decompose the regulated variables y into two parts, y_1 and y_2, and assume that y_2 contains the variables which are important but not well controlled by the existing controllers. In the same way, we decompose the original controller output u and the reference signals r into two parts accordingly, as shown in Figure 2.

It is easy to derive the following relations:

$$y = \left(I + P_{us}\begin{bmatrix} 0 & 0 \\ 0 & C_s \end{bmatrix}\right)^{-1}(P_{rs}r+P_{ds}d) \tag{8}$$

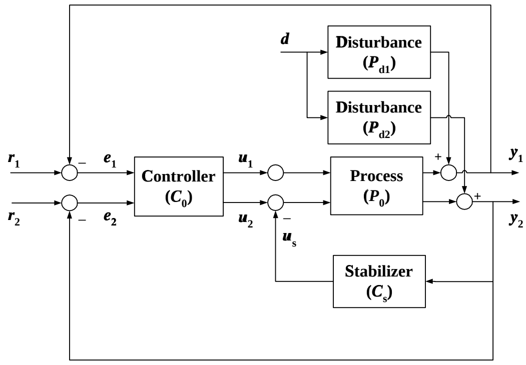


Fig. 2. Stabilizer configuration II

where

$$y = \begin{pmatrix} y_1 \\ y_2 \end{pmatrix}, u = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix}, r = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}, P_d = \begin{bmatrix} P_{d1} \\ P_{d2} \end{bmatrix} \tag{9}$$

and P_{us}, P_{rs} and P_{ds} are defined in (4). Suppose they are decomposed accordingly:

$$P_{us} = \begin{bmatrix} P_{us11} & P_{us12} \\ P_{us21} & P_{us22} \end{bmatrix}, P_{rs} = \begin{bmatrix} P_{rs11} & P_{rs12} \\ P_{rs21} & P_{rs22} \end{bmatrix},$$
$$P_{ds} = \begin{bmatrix} P_{ds1} \\ P_{ds2} \end{bmatrix}$$

Then we have

$$\begin{aligned} y_2 &= (I+P_{us22}C_s)^{-1}(P_{rs21}r_1+P_{rs22}r_2+P_{ds2}d) \\ u_s &= C_s(I+P_{us22}C_s)^{-1}(P_{rs21}r_1+P_{rs22}r_2+P_{ds2}d) \end{aligned}$$

We can design a stabilizer in this case by solving similar problems as above.

It should be noted that P_{us22}, P_{rs22}, and P_{ds2} are simply the *closed-loop* transfer functions from u_2, r_2, and d to y_2, respectively. We should also note that y_1 will be affected when using a stabilizer. Since our design procedure ignores this coupling effect, the addition of the stabilizer is not guaranteed to bring an improvement in the performance of this variable. By assumption, however, y_1 is somewhat less important than y_2, and we are willing to tolerate some deterioration in the performance of y_1 if the counter benefits in y_2 are significant.

3. STABILIZER DESIGN FOR THE SYNCRUDE PLANT

As was stated in the previous Section, the purpose of the boiler control system for Syncrude utility plant is to track the steam load while maintain the steam pressure and the steam temperature of the 900# header. To accomplish this task we propose to improve the performance of the system via a stabilizer as discussed in the Section 2. To proceed, first we need to consider which variables should be used as the stabilizer input variables, and which variables can be corrected by the stabilizer. Some of the most significant variables in the plant are the following:

- Total steam flow rate
- Steam pressure of the 900# header
- Steam temperature of the 900# header
- Steam pressures of the 600#, 150# and 50# headers
- Drum level of the utility boilers
- Drum level of the CO-type boilers

The total steam flow rate measures the quantity of the steam generated by the boiler system, and the steam pressure and temperature of the 900# header measure the quality of the steam; the setpoints for these two variables are determined by the electricity generating system and the extraction process. The steam of the other three headers is used for other plant utilities such as process heating, fluidization, and building heating. The drum level for the boilers are important for the sake of safety. To control these variables the following corresponding control variables are used in the present control system:

- Firing rate of the CO-type boilers
- Firing rate of the utility boilers
- Feedwater flow rate of the once-through boilers
- Control valves of the back-pressure turbines and the letdown valves at 600#, 150# and 50# headers
- Feedwater flow rate of the utility boilers
- Feedwater flow rate of the CO-type boilers

Although all of the variables listed above are important for normal plant operation, in the stabilizer design we will choose the 900# header pressure as the most important variable, the reasons are as follows:

(1) The drum level control is usually regarded as a separated control system, and is thus independent of other control loops.
(2) The response for the total steam flow rate was found to be acceptable in the existing control system.
(3) The steam pressures of the 600#, 150# and 50# headers are related to the 900# header pressure. If the 900# header pressure is maintained well, so will the pressures of the other three headers. Furthermore, the control for these pressures is acceptable in the existing control system.
(4) The steam temperature of the 900# header is also an important variable and should be included in the stabilizer design. However, currently its variation is tolerable in the plant operation. So to simplify the design we choose to ignore it. As we will see from the simulation results later, as the steam pressure response is improved, so is the steam temperature response.

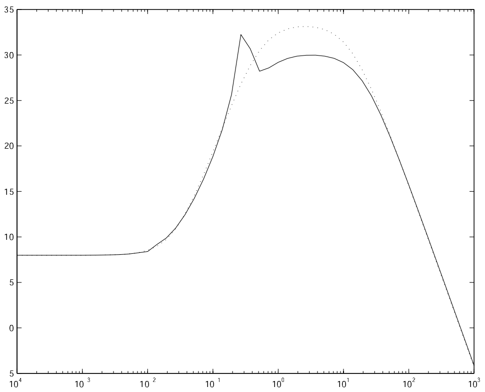
So the 900# header pressure is the object of our stabilizer design. This selection is also emphasized by the fact, well established in control theory, that sensitivity reduction (with respect to parameter variation) can only be achieved with respect to those measured variables used for feedback. Once this variable is selected, we now recognize that, for physical reasons, the firing rate of the utility boilers is the natural control variable. Our problem is to regulate 900# header steam pressure against steam load changes, which corresponds to a disturbance rejection problem. We will use Configuration III and proceed with the design by solving (7) with y_2 as the 900# header pressure and u_2 as the utility boiler firing rate. In order to apply the procedure of Section 2, we need to identify the closed-loop transfer functions from steam load to the 900# header pressure and from the firing rate of the utility boilers to 900# header pressure. To identify the desired plant model we proceed as follows: at a steady operating point, where each utility boiler produces 515 KPPH steam, using SYNSIM we manually added a small control effort on the utility boiler firing rate controller output and let the system run for a period of time and record the input and output concerned. After filtering the data, by trial and error, using the MATLAB Identification Toolbox (Ljung, 1988), we find that a 5th-order OE model gives the best identification results. The identified model using the toolbox is in the discrete-time domain. To make use of the continuous-time H_∞ design, we transform the discrete-time model to a continuous-time model using the Tustin's approximation. The same procedure was used to obtain the closed-loop transfer function from steam load to 900# header pressure. Using these transfer functions we can now proceed with the design. Since the steam load change is usually restricted in speed in plant operation, we need only to consider constant weights. By choosing $W_3 = 8$, $W_4 = 4$, we solved the H_∞ optimization problem (7) using the state-space solution introduced by Doyle *et al.* (1989). Using this approach,we obtained

$$\inf_{C_s} \left\| \begin{matrix} W_3(I+P_{rs}C_s)^{-1}P_{ds} \\ W_4C_0C_s(I+P_{rs}C_s)^{-1}P_{ds} \end{matrix} \right\|_\infty = 1.25$$

The order of the resulting controller is seven, which is rather complex to be implement with the present control hardware. Several techniques [e.g., the balanced truncation method (Pernebo and Silverman, 1982) and the Hankel norm approximation method (Glover, 1984)] can be used to reduce the order of the H_∞ controller. Here we use the coprime factor model reduction technique (McFarlane and Glover, 1990). By performing a balanced realization of the normalized left and right coprime factors of the controller, we note that the first two Hankel singular values of the controller are 0.6959 and 0.1779, while the other 5 are less than 0.0175, so we can reduce the controller to a second order one. The final 2nd-order controller is

$$C_s(s) = \frac{609.35s + 16.71}{s^2 + 13.4234s + 6.6689} \tag{10}$$

The singular value plots of the 7th-order controller and the reduced 2nd-order controller are shown in Figure 3. It can be noted that in the desired frequency band they are fairly close to each other, and the performances of these two controllers are thus expected to be similar.



(solid: 7th-order; dotted: 2nd-order)

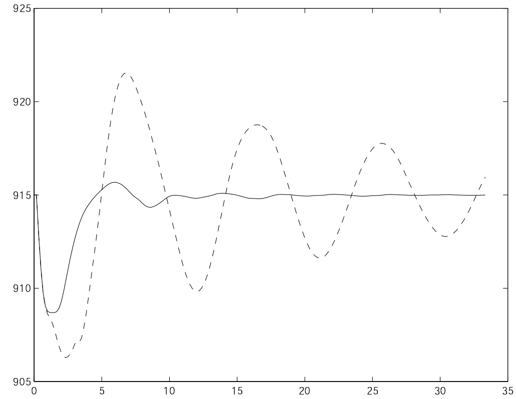
Fig. 3. Singular value plots of the stabilizers (dB) vs. frequency (rad/s)

4. SIMULATIONS

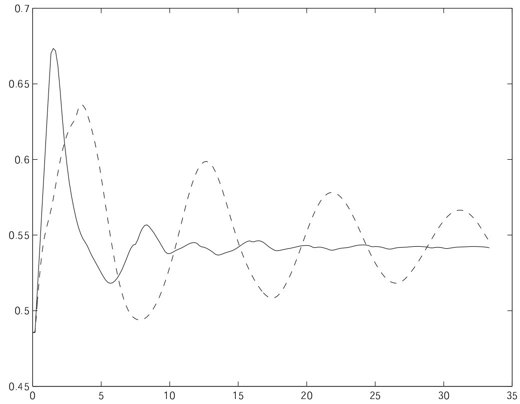
In order to test our design, we now show simulation results under several conditions. Before proceeding to discuss our results we notice that while the true plant is nonlinear and rather complex, the model used in the design and therefore the resulting controller are linear time-invariant and of a relatively low order. It is therefore important to simulate the results under realistic assumptions and using a tool that, as closely as possible, resembles the complexity of the true plant. It is here where we rely on the power of SYNSIM. Indeed, simulation results shown here are fully expected to be close to actual implementation results.

Since the objective of our design is to improve disturbance rejection in the response of the 900# header pressure, the principal test to be conducted is how well this variable responds to load changes. Using SYNSIM, and with the plant at the nominal operating point, we model a steam load increase of 100 KPPH. Figure 4(a) shows the 900# header pressure responses to this change, with and without the stabilizer. We find that the header pressure has a much smoother response when using stabilizer. More importantly, the disturbance rejection capabilities of the system with the stabilizer are much improved both in term of *speed* and *amplitude*. Also the maximum deviation from nominal conditions (or the lowest point in the time response shown in Figure 4(a)) is also smaller than that without stabilizer.

From this test we thus conclude that the stabilizer indeed improves the disturbance rejection property of the closed-loop system. Figure 4(b) shows the firing rate of the utility boiler corresponding to the same load change, which is the control variable used in our design. The figure shows a much more aggressive control action, which helps to explain the improvement shown in disturbance rejection. To evaluate the possible side effects of this control action we simulate the effect of the same load change on the other variables identified



(a) 900# header steam pressure (psi) vs. time (min.)



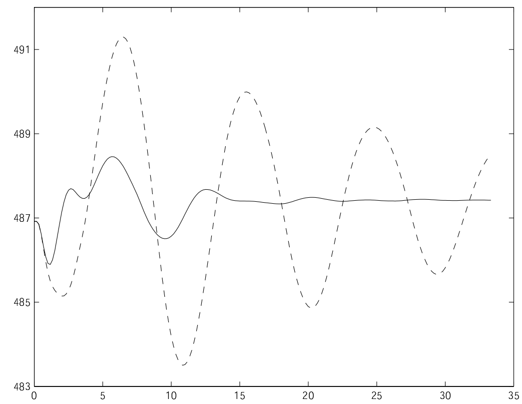
(b) Firing rate of each utility boiler vs. time (min.)

Fig. 4. Responses of 900# header pressure for step change of steam load at nominal load (solid: with stabilizer; dashed: without stabilizer)

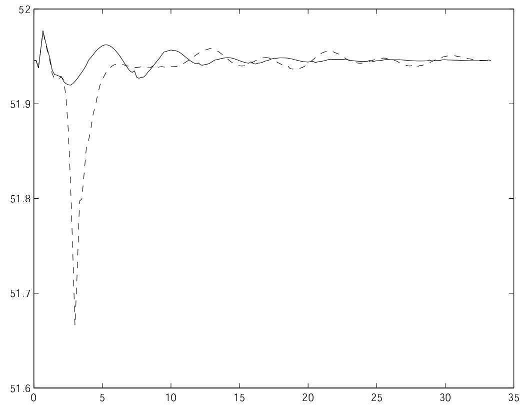
in Section 3 as the *important variables*. As mentioned, each one of these variables has a significant role in the plant operation.

Figure 5 shows the response prompted by the same load change on the 900# header steam temperature, and the 50# header steam pressure. From the figure we see that the response for the 900# header steam temperature is also improved. More importantly, the 50# header steam pressure shows a sharp improvement. This is a very significant improvement in the power generation since the 50# header pressure is the back pressure affecting the turbines. Thus the tighter control of this pressure also contributes to the production of energy at a constant rate.

From the discussion in Section 3, we see that to further improve the system performance, we should take into account the multivariable nature of the system and investigate multivariable design. For a multivariable design, the output variables should include all the variables mentioned in Section 3, so the plant model will have 8 inputs and 8 outputs. If we treat the drum level control as a separate system, the model will be reduced to 6×6. Further, if we only focus on 900# header, we get a 3×3 model. The design procedure for such a system was discussed in (Tan *et al.*, 2000). Figure 6 shows a comparison of the response of the



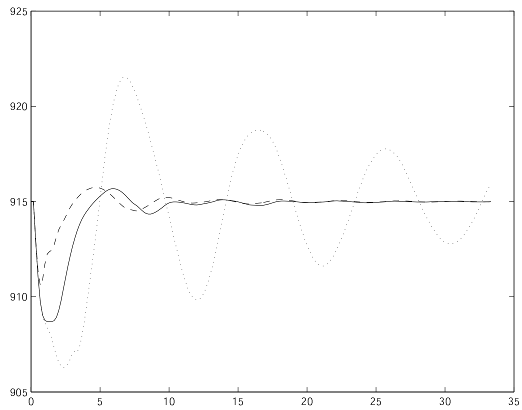
(a) 900# header steam temperature (^{o}C) vs. time (min.)



(b) 50# header steam pressure (psi) vs. time (min.)

Fig. 5. Responses of other variables for step change of steam load at nominal load (solid: with stabilizer; dashed: without stabilizer)

900# header pressure against a step increase of 100 KPPH on 900# header steam load for the designed multivariable controller and the designed stabilizer. It is obvious that the multivariable controller can reject the disturbance rather quickly, and so it is superior to the stabilizer. The disadvantage is that it is much more complex and hence harder to implement.



900# header pressure (psi) vs. time (min.)

Fig. 6. Comparison of different control systems (dashed: multivariable controller; solid: with stabilizer; dotted: without stabilizer)

5. CONCLUSIONS

A stabilizer design procedure is proposed to improve tracking and disturbance rejection performance for existing complex control systems. The approach is simple to apply and need only some of the closed-loop transfer functions from existing systems. Application of the approach in the Syncrude utility plant shows that it can indeed improve the disturbance rejection performance and the stabilizer is simple to implement and test in practice.

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