Drive-by-Wire Control of Automotive Driveline Oscillations by Response Surface Methodology

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***Abstract*—The first torsional mode (otherwise known as "shuffle" mode) of automotive drivelines is excited by engine torque transients and is typically around 2–5 Hz. The effect is particularly severe during step changes from the throttle pedal ("tip-in" or "tip-out"). Shuffle is manifest as a low-frequency longtitudinal acceleration oscillation which, if of sufficient magnitude, leads to driver discomfort. This brief examines the control of this aspect of "driveability" (the error between expected vehicle response and actual vehicle response to an arbitary control input) using feedforward control. The overriding principle to be obtained in this examination is the assessment of electronic throttle control in the context of rapid prototyping. The response surface methodology is adopted to achieve this goal. The potential of the electronic throttle for launch control is analyzed and investigated experimentally, confirming its effectiveness in controlling the first torsional mode.**

***Index Terms*—Driveability, driveline, predictive, response surface, shuffle.**

I. Introduction

THIS BRIEF documents the investigation of the performance potential of a low-cost electronic throttle actuator and microcontroller development to control vehicle oscillation. Aside from cost, rapid prototyping was an important factor in the feasibility study. As the hardware was extant before the development of control strategies (as is common in many development projects), the important question, "can the project objectives be achieved with the existing hardware?" needs to be answered early to allow for hardware changes, and to avoid excessive time being wasted in control-system design. The response surface methodology (RSM) was adopted in the context of rapid prototyping to confirm: 1) the suitability of the actuator and 2) the existence of appropriate control signals, which is an essential tool for high-budget delivery critical design projects. Further, the RSM design is finally adopted as the chosen controller due to its simplicity and hence, computational economy in the context of processing constraints. If a set of trajectories (in this case) for the throttle movement can be identified that achieve the required design objectives, then the control system design can be pursued with an increased level of confidence. The existence of an open-loop solution does not absolutely guarantee that the same results can be obtained through a closed-loop controller, only that the control trajectories exist to achieve the desired performance. Furthermore, if these trajectories can be achieved by closed-loop control, then the actuator bandwidth and dynamics will be sufficient to achieve this performance. Designed experiments are implemented to confirm the existence of the appropriate trajectories, which are then confirmed experimentally. For reasons of robustness, it would be preferred for the final control structure to be closed-loop, however, in the context of a pressing need for rapid prototyping, the RSM method is shown to be invaluable.

Drive by wire applications, for the replacement of the conventional cable link between the throttle pedal and the throttle body, are now the focus of development for many major automotive manufacturers. By fitting a stepper or permanent magnet servo motor [14] to the throttle body, and an electronic throttle pedal with potentiometer, a "drive-by-wire" system can be implemented with no more than a simple linear amplifier. If a microcontroller or digital signal processor (DSP) is added to the system, then sophisticated control algorithms can be added to the operation of the throttle [15]. Control systems have been designed [12], which allow fast and accurate response to changes in pedal demand, and have been shown to possess robust operating characteristics. The control inputs available to control the typical performance objectives are: throttle position, fuel injection timing, exhaust gas recirculation and ignition timing. Current trends indicate that electronic throttle control and variable valve timing are the focus of intense development [1], [13]. A torque controller is designed and implemented in this brief to shape the vehicle response to the first-torsional mode of the driveline. The initial requirement is to damp the oscillations generated by throttle tip-in. This dynamic mapping is constrained by the requirement to maintain, where possible, the vehicle acceleration response available to the throttle. Control analysis and design for this automotive system is complicated by a number of factors. There are a number of nonlinearities present, such as backlash in the gearbox, a tyre force which varies nonlinearly with road speed, and nonlinear clutch response. Added to which, is a process lag between throttle actuation and torque production and nonlinear engine torque speed mapping [6]. The control algorithm is required to reside initially for prototyping purposes on an Intel 8XC196KC 16-b microcontroller which imposes constraints on the memory size and execution time available to the controller. A more powerful processing platform will be made available if necessary. Experimental data is available from a test car which was fitted with a data acquisition system including three axis accelerometers. A V6–engine saloon vehicle was loaned for the purpose of analysis, design and, testing. The design brief was, in essence, to implement a control scheme to fit within the memory space of the microcontroller and demonstrate the potential application of electronic throttle control to damp driveline launch vibrations. Al-

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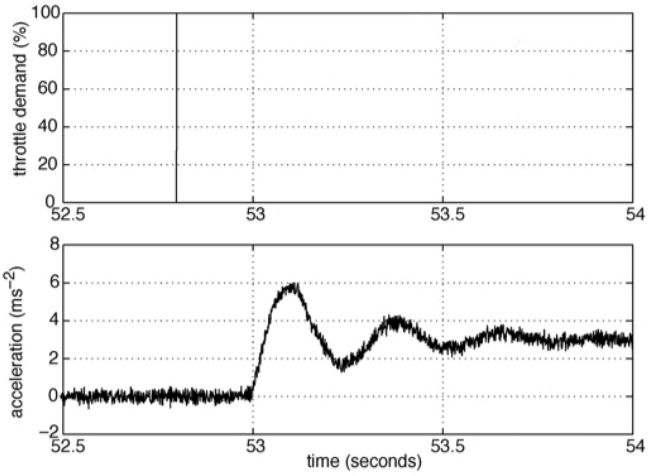

Fig. 1. Vehicle acceleration step response in second gear at 10 ms^{-1}.

though accelerometers were available for experimental verification, in the first instance it was desired that only signals and measurements available on a standard unmodified car be used in the control system. A systematic excitation of the driveline was made experimentally on the vehicle by performing step demands in all gears at discrete points throughout the effective engine-speed range of the vehicle. The generated experimental data (road speed, acceleration, engine speed etc.) was analyzed using the RSM [8]. The method allows the exploration and optimization of response surfaces, where the response variable of interest (for example vehicle acceleration) is related to a set of predictor variables (for example road speed, selected gear). In the development of a model and control system constrained by computational considerations, and the requirement of rapid prototyping, the RSM allows a low-order approximation to be derived from empirical data [16] by the method of least squares. A reduced-order representation can then be employed in the controller. Application of the RSM analysis to the vehicle response data allows a system model to be developed which lends itself to the design of a scheduled controller structure which is shown to control the first torsional mode of the driveline.

II. RSM APPLICATION

In the analysis of the acceleration response of the vehicle, there are three variables of interest, namely vehicle loading, road speed, and selected gear ratio. For the purpose of clarity in the description, vehicle loading will be assumed to be a fixed standard two person loading of 160 kg. In order to reduce the overall number of data sets required to construct the response surface of the system, a factorial approach is adopted [5]. The combinations of factorial experiments at 5 ms^{-1} in each gear requires 25 experiments to be performed. Each proposed factorial combination was assigned a serial number and performed in random order via output from a random number generator. Each experiment consists of coasting the vehicle in the appropriate gear at the appropriate roadspeed, and performing a 100% tip-in with the accelerator pedal. On the day of testing, the one mile asphalt test road was dry, with overcast sky and ambient temperature of 60°F. The effect of the energy storage components in the driveline can be clearly seen in an examination of the vehicle at 10 ms^{-1} in second gear in Fig. 1. Examination of the vehicle response to tip-in reveals a system which can be approximated as a delay and second-order dynamic response with an overshoot and settling time which varies with road speed and selected gear. This approximation to describe the entire vehicle response can be formulated by application of RSM to the experimental data. Of note is also the lag between actuation and response. The torque lag is combined with a high level of lash for this high-mileage vehicle

The experimental data which has been gathered can be synthesised into a response map for the vehicle in order to design an oscillation control system. For the definition of driveability under consideration here, the vehicle response can be characterized as the damping ratio of the second-order approximation map with variables road speed and selected gear. The individual experimental responses may be expressed in terms of overshoot and settling time. The transfer function describing the open-loop system may be described as

$$\frac{C(s)}{R(s)} = k\frac{1}{as^2 + bs + c} \tag{1}$$

from which the damping ratio of the system can be calculated as the ratio of the actual damping b to the critical damping $b_c = 2\sqrt{ac}$ [9]. Thus, the damping ratio ζ can be calculated from $\zeta = (b/b_c)$. The roots of the characteristic (1) are s_1, $s_2 = -b_c \pm jc\sqrt{1 - b_c^2}$. This forms a complex conjugate pair from which the damping ratio and natural frequency can be computed. The natural units ξ_1 and ξ_2 of the experimental data (road speed and selected gear) is first transformed into the corresponding normalized coded variables x_1 and x_2, such that

$$x_{i1} = \frac{\xi_{i1} - \frac{[\max(\xi_{i1}) + \min(\xi_{i1})]}{2}}{\frac{[\max(\xi_{i1}) - \min(\xi_{i1})]}{2}} \tag{2}$$

and

$$x_{i2} = \frac{\xi_{i2} - \frac{[\max(\xi_{i2}) + \min(\xi_{i2})]}{2}}{\frac{[\max(\xi_{i2}) - \min(\xi_{i2})]}{2}}. \tag{3}$$

The model can be expressed in matrix form as [8]

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon} \tag{4}$$

where

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \cdot \\ \cdot \\ \cdot \\ y_n \end{bmatrix} \quad \mathbf{X} = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix}$$
$$\boldsymbol{\beta} = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \cdot \\ \cdot \\ \cdot \\ \beta_n \end{bmatrix} \quad \boldsymbol{\epsilon} = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \cdot \\ \cdot \\ \cdot \\ \epsilon_n \end{bmatrix}. \tag{5}$$

It is now necessary to find a vector of least squares estimators $\mathbf{b}$ which minimizes the expression

$$L = \sum_{i=1}^{n} \boldsymbol{\epsilon}_i^2 = \boldsymbol{\epsilon}'\boldsymbol{\epsilon} = (\mathbf{y} - \mathbf{X}\boldsymbol{\beta})'(\mathbf{y} - \mathbf{X}\boldsymbol{\beta}) \tag{6}$$

and yields the least-squares estimator of $\boldsymbol{\beta}$ which is

$$\mathbf{b} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y} \tag{7}$$

and finally, the fitted regression model is

$$\hat{\mathbf{y}} = \mathbf{X}\mathbf{b}, \quad \mathbf{e} = \mathbf{y} - \hat{\mathbf{y}} \tag{8}$$

where $\mathbf{e}$ is the vector of residual errors of the model.

The second-order model to be fitted to the data is

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \epsilon. \tag{9}$$

Utilizing (5)–(8), we obtain the coefficient matrix

$$b = \begin{bmatrix} 0.4079 \\ -0.804 \\ 0.3809 \\ 0.0519 \\ -0.0429 \\ -0.0121 \end{bmatrix} \tag{10}$$

therefore, the response surface in terms of the coded variables is obtained

$$\hat{y} = 0.4079 - 0.804x_1 + 0.3809x_2 + 0.0519x_1^2 - 0.0429x_2^2 - 0.0121x_1x_2. \tag{11}$$

Comparing the computed response surface against a second experimental data set gave an average residual error of 1.65%. The design of the prototype driveability compensator will be considered in the next section.

III. Controller Design

The control of driveline shuffle has been the subject of controller design, including LQR and generalized optimal control (GOP) [2] noting that the technique is "unlikely to prove beneficial in any practical implementation of driveline control", and pole placement [10], [11], which utilizes a ninth-order controller which although damping the decay oscillations, adds an undesirable initial acceleration transient.

As previously noted, it is required to assess the usefulness of RSM for rapid prototyping, and also to provide an initial simple useable controller to identify the potential of the electronically operated throttle body for controlling the driveline. The simple feedforward controller is designed as follows. A response surface has been obtained which describes accurately the vehicle's damping ratio map. As an initial design target, a damping ratio of 0.7 across the entire operating map would be a desirable response. The problem as presented to the control designer is nonlinear and time variant (varying with selected gear and roadspeed), a transport delay exists in terms of engine torque production, and the engine torque output varies nonlinearly in terms of engine speed, engine temperature and other factors. The RSM analysis however allows a simple open-loop feedforward controller to be immediately designed and implemented to allow a fast appraisal of the actuator potential. The system response surface extracted from the experimental data is a representation of the complex conjugate pole pairs of the approximation (Fig. 2) in terms of the system's varying damping ratio. The initial approach will be to effect a pole-zero cancellation of these complex conjugate poles to give a satisfactory response. This method does rely on accurate knowledge of the position of the uncompensated poles which has been ascertained experimentally for the purpose of this development. The parameters of the feedforward controller are derived in real-time from the response surfaces and are a function of selected gear and roadspeed. The feedforward compensator takes the form $(as^2 + bs + c)/(as^2 + ds + c)$ where the coefficient b is calculated from the damping ratio response surface, and performs pole-zero cancellation. Coefficient d produces the desired pole placement and forms the required damping ratio.

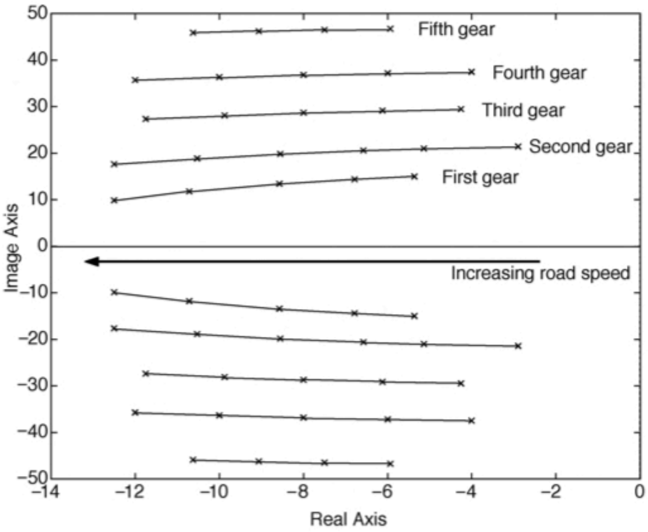

Fig. 2. Vehicle complex-conjugate pole map.

The control scheme was implemented on the microcontroller in assembly language, to ensure the fastest execution time, and took the form of three modules:

- calculate damping coefficient from current roadspeed and selected gear;
- calculate damping error;
- update numerator and denominator coefficients.

The demand from the throttle pedal, throttle position, and roadspeed were read in via A/D ports, and the selected gear read in via the digital I/O. Output from the controller was sent to a power amplifier via the pulsewidth modulation (PWM) port. With the controller in place, the experimental set was repeated to assess the potential of the electronic throttle control.

IV. Experimental Results

Of particular note in this implementation is the fact that the hardware assembled to achieve the electronic throttle control is both cheap and readily available. The goal of rapid prototyping was achieved in a matter of days between initial experimental testing and final implementation testing. The original set of experiments were repeated with the electronic throttle both compensated and uncompensated. A comparison at the 10 ms^{-1} in second gear step response is shown in Fig. 3. The time axis in both traces was zeroed at the initiation of the step demand for the purpose of clarity. The marked improvement in vehicle oscillation obvious in Fig. 3 was repeated throughout the operating map of the vehicle. The smooth acceleration response is in marked contrast to the results achieved with (for example)

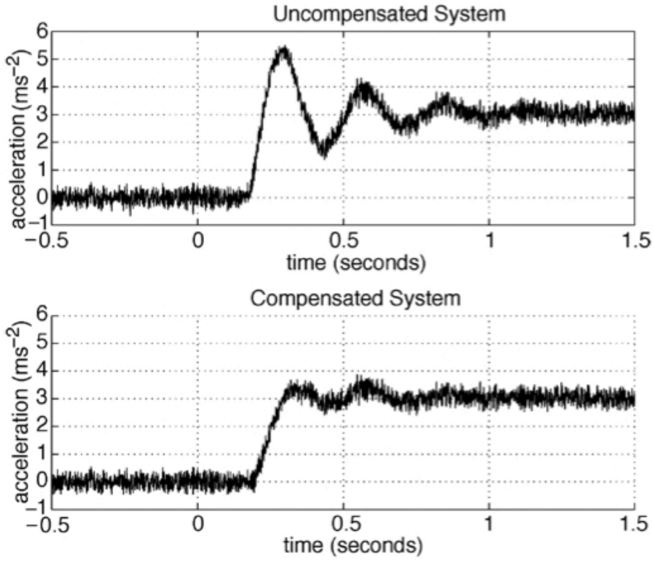

Fig. 3. Vehicle compensated and uncompensated step response.

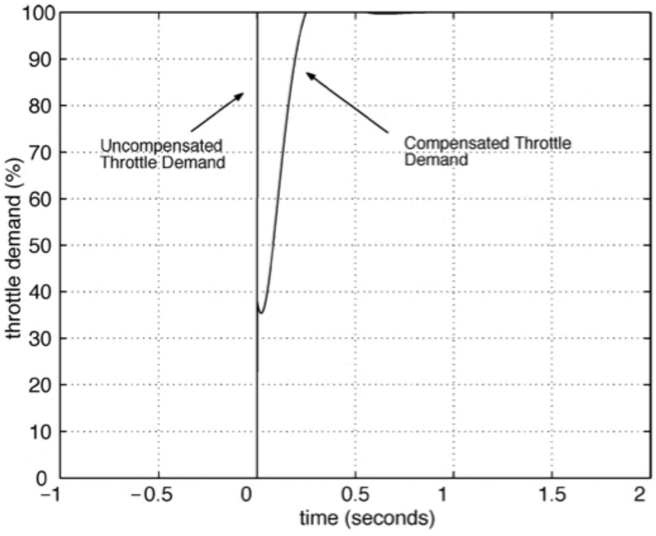

Fig. 4. Uncompensated and compensated throttle demands.

polynomial pole placement techniques [11] in which oscillation is present in the rising acceleration trajectory. The throttle demand computed by the algorithm at the operating point in Fig. 3 is shown in Fig. 4. The compensated vehicle responses over the operating region of the vehicle were found to have a mean damping ratio of 0.68, with a maximum residual of 0.07. The tip-in driveability of the vehicle was found to be subjectively very improved, in addition to the experimental evidence of the vehicle compensated step response. Although a small amount of acceleration rate is sacrificed to achieve the supression of oscillations subjectively the vehicles performance was not felt to be affected. The controller did endow the vehicle with a "turbine-like" (a smooth positive rise in acceleration without any associated oscillations) feel. A further robustness study in simulation further supported the experimental results in (Figs. 5 and 6).

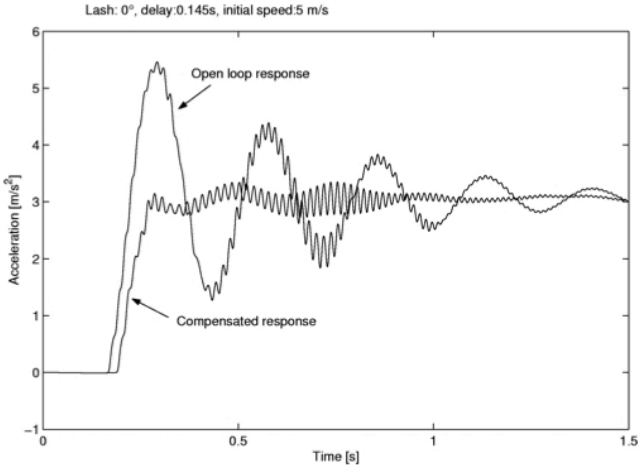

Fig. 5. Vehicle acceleration response, $\text{lash} = 0$, $\text{delay} = 145$ ms, $\text{initial speed} = 5\ \text{m/s}$.

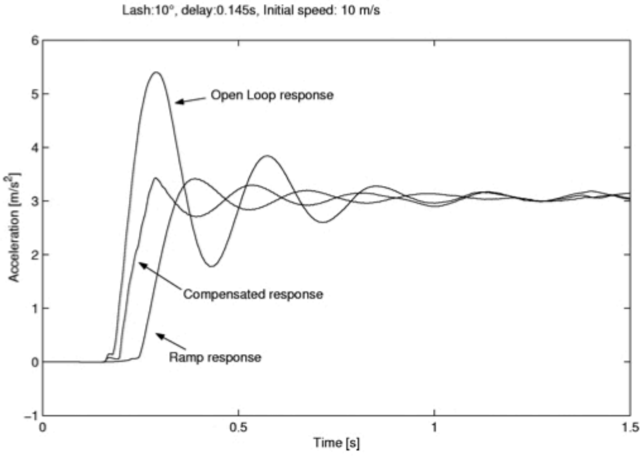

Fig. 6. Vehicle acceleration response, $\text{lash} = 10^\circ$, $\text{delay} = 145$ ms, $\text{initial speed} = 10\ \text{m/s}$.

V. CONCLUSION

This project had two hierarchically related objectives, first to examine the application of the RSM to rapid control design prototyping, and having successfully achieved this goal, the second objective was to use the RSM to examine the potential of electronic throttle control to shape the acceleration response of an experimental vehicle. At no point is the application of RSM being suggested as a replacement for standard control design procedures, however the benefits of its addition to the controller designer's toolbox become immediately apparent when we consider the design process presented in this brief. The timescale from experimental data capture through RSM analysis to experimental verification and assessment of the electronic throttle's potential for vehicle acceleration shaping was under four days. At this point, a judgement upon the viability and potential of the project could easily be made with confidence. In parallel with the RSM analysis, standard controller designs were being implemented and assessed. It is necessary to develop a fully dynamic model in a software simulation package such as Simulink. The development of the mathematical models in conjunction with a simulation and also highly complex nonlinear controller design is by its nature an extremely time consuming task. In this context, the use of the RSM becomes extremely attractive. The technique has allowed an examination of the system control potential to be made at the start of the project, benefitting both the confidence of the industrial partners, and giving a realistic benchmark of potential performance. The controller derived by the RSM is immediately useable on the experimental vehicle, providing a demonstration facility at project inception. Some other benefits of this development tool are also significant. A controller is quickly available for verifying the mechanical and electrical components of the control system, giving a stable platform for subsequent controllers as and when they become available. The controller as designed via the RSM is simple and low-order by nature, and thus, can be installed on a very simple microcontroller. Finally, a quick and cheap assessment of a system's potential can be rapidly made in order to support project development proposals. A controller has been developed to examine the potential of electronic throttle control. The stated requirements were rapid prototyping, algorithm simplicity in both design and implementation, oscillation control, and the ability to work effectively across the entire operating region of the vehicle. All these requirements have been fulfilled, with the conclusion that electronic throttle control is a capable tool in a suite of applications to control the various aspects of "driveability." A secondary achievement has been to implement the control system on extremely cheap widely available components, further adding to its attractiveness. A design method has been followed, centered around the RSM which has enabled the rapid prototyping process from empirical data. The design of a useable implementation has been achieved on a time-varying process with significant time delays and nonlinearities.

APPENDIX

A feedback driveline controller was subsequently developed using the pole-placement method. Multiobjective search techniques [7] using evolutionary algorithms were applied [4] to find a control design robust to environmental and parameter variations (such as road surface and gear lash) [17]. Design objectives were rise time, settling time, and control action. A signal from a longtitudinal accelerometer was used for closing the feedback loop. The controlled throttle trajectory response time is approximately equal to the lag between system input and output. Consequently a model predictive control scheme [3] allowing control action to be calculated, based upon response predicted by an internal model was implemented. The acceleration responses of the vehicle for two example initial conditions are shown in Figs. 5 and 6: the response of the designed feedback controller exhibits characteristics predicted by the RSM designed feedforward controller, demonstrating the link and similarity between open-loop and closed-loop control signals. In Fig. 6, comparison is also made to the simplest controller strategy, which is the tracking of a reference ramp signal. Although the ramp controller achieves oscillation control, the response lag is unacceptable. The early application of designed experiments had identified that a population of throttle trajectories did in fact exist to satisfy the design response objectives. This allowed the subsequent control design for the platform to be pursued with confidence. Based upon the computational intensiveness of the closed-loop controller, the RSM designed control scheme was adopted as the *de facto* controller due to its simplicity and computational economy.

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