In-Service Diagnostics of Motor-Operated Valves

David L. Bowen and Richard H. Lyon

RH Lyon Corp, 691 Concord Ave, Cambridge, Mass. (USA) Fax: 617 864 0779 Ph: 617 864 7260

Introduction

This article describes two different but complementary non-intrusive methods for determining forces and motions in motors and gearing systems, with application to the in-service diagnostics of motor-operated valves (MOVs). Such valves employ a motor and gearing system to remotely open or close a valve, and are widely used in the power generation, chemical processing and wastewater treatment industries. One method is the determination of instantaneous torque in 3-phase induction motors using line voltages and currents. The second is the determination of gear rotations by analyzing the housing vibrations that they produce. In-service diagnostics of MOVs can improve the safety and readiness of a plant by improving the repair, maintenance and operating procedures in the plant. Parameters tracked with a non-invasive diagnostic method can be used to make decisions regarding repair of the valve in use.

Research on the combined use of electrical and vibration signals for the diagnostics of MOVs was originally conducted at M.I.T. under support from a consortium of nuclear power industry members, and some basic procedures for estimating motor torque and valve travel in laboratory situations were developed there [1]. During subsequent work performed by RH Lyon Corp under support from the U.S. Nuclear Regulatory Commission, these procedures were tested and refined using a larger class of fault conditions and operating environments.

Although the two methods are combined in MOV diagnostics, each has its own areas of application beyond MOVs. Induction motor torque measurement has applications in the production and use of such motors in transportation, construction, and manufacturing. Vibration based motion determination has applications for both the control of and performance monitoring of position control systems.

Estimation of Motor Torque from Electrical Signals

The conceptual basis for using line voltages and currents to determine torques is fairly elementary. In a balanced 3-phase motor, torque is the product of flux linkage and stator winding current. Since the winding currents are known, and the flux linkages can be determined from line voltages, the torque can be calculated. The application of torque estimation described below is to MOV's, but induction motors are used in many applications where their performance and condition are essential to operations. Elevators and other people movers, electric automobiles and trains, drive rolls for paper making, and many other areas can benefit from this non-invasive procedure.

In outline form, the procedure for calculating the instantaneous motor torque from measured current and voltage signals is as follows:

1. The rate of change in flux linkage is found by subtracting the IR drop from the measured voltages, where I indicates the measured currents and R the measured DC resistance of the windings.
2. Flux linkage itself is found by integrating its derivative found above in Step 1; the unknown initial condition for the flux linkage is removed via a "forgetting factor" parameterization procedure. We have developed this procedure to be very insensitive to the forgetting factor, meaning that a single value can be used for various size MOV motors.
3. Motor torque at the air gap is then found from the product of current and flux linkage.

The torque estimation procedure is presently set up to work with any three-phase induction motor, and is based on the following assumptions: (1) the stator and rotor windings are sinusoidally wound, coupling only to the fundamental space harmonic component, (2) self-inductance of the windings does not vary with rotor position; mutual inductances between rotor and stator vary sinusoidally, (3) motor core losses are neglected (the estimated value is the torque at the motor air gap), (4) linear magnetics are assumed, (5) motor configuration and line voltages are balanced, and magnetic saturation is localized and constant. Since these assumptions may lead to neglected losses in the motor, the procedure will tend to provide an upper-bound estimate of the actual motor shaft torque (as would be measured, for example, by a dynamometer). We have found, however, that with most motors this difference is negligible, and in any case can be related if the dynamics of the rotor and the load are known.

Estimation of Gear Rotation and Valve Travel from Operator Casing Vibration

The gear rotation procedure uses housing vibrations that are induced by motor pinion gear mesh forces. In simple terms, the meshing frequency is determined by spectral analyses to determine the instantaneous (actually, averaged over a short interval) frequency of gear rotation. This instantaneous frequency is then integrated to obtain gear rotation, and therefore, the motion and position of attached mechanisms. In an MOV, the motion of interest is valve travel.

The MOV vibration signal used to determine valve displacement is obtained from an accelerometer mounted on the actuator casing. The routines have been configured for MOVs that have a double reduction gear set, such as found on Limitorque® actuators. The bulk of the vibration analysis procedure involve specialized routines that ensure accurate tracking of the motor pinion gear mesh frequency over time. The pinion mesh is tracked, rather than the more direct worm gear mesh, since its higher frequency generally makes it less susceptible to contamination by flow-induced noise or other residual vibration, and we can track it with greater precision than we could the lower frequency worm mesh. Once the final pinion mesh frequency estimates are available, they are then converted into valve displacements via time integration and knowledge of the gear ratios and stem lead for the particular MOV under test.

To track pinion mesh, we started out using a method originally outlined by Lerch [3], but found it necessary to increase the "robustness" of the method by revising the zoomed autoregressive modeling portion to include both the fundamental pinion gear mesh frequency and its first harmonic, increasing the length of each time "slice" over which a position estimate is obtained to approximately every ½ second. We also made use of a moving average of the spectral energy at the calculated pinion mesh frequency in order to determine whether or not the gears were rotating.

In outline form, the basic structure of the algorithm for extracting valve stem travel from the digitized output of the vibration sensor is as follows:

A) For each “time slice” of the measured acceleration signal:

1. Bandpass filter the acceleration signal around the expected nominal pinion mesh freq., where the width of the filter depends on the nominal worm mesh frequency.
2. Compute spectrum of filtered segment, after Hanning windowing and zero padding it.
3. Compute autocorrelation sequence of “zoomed” power spectrum (i.e., between bandpass filter settings, after increasing length to a power of 2 if necessary).
4. Use a Levinson-Durbin iteration to perform autoregressive (AR) modeling of the zoomed autocorrelation sequence determined in Step 3, subject to some maximum order.
5. Compute autospectrum, H_0, of resulting AR coefficients.

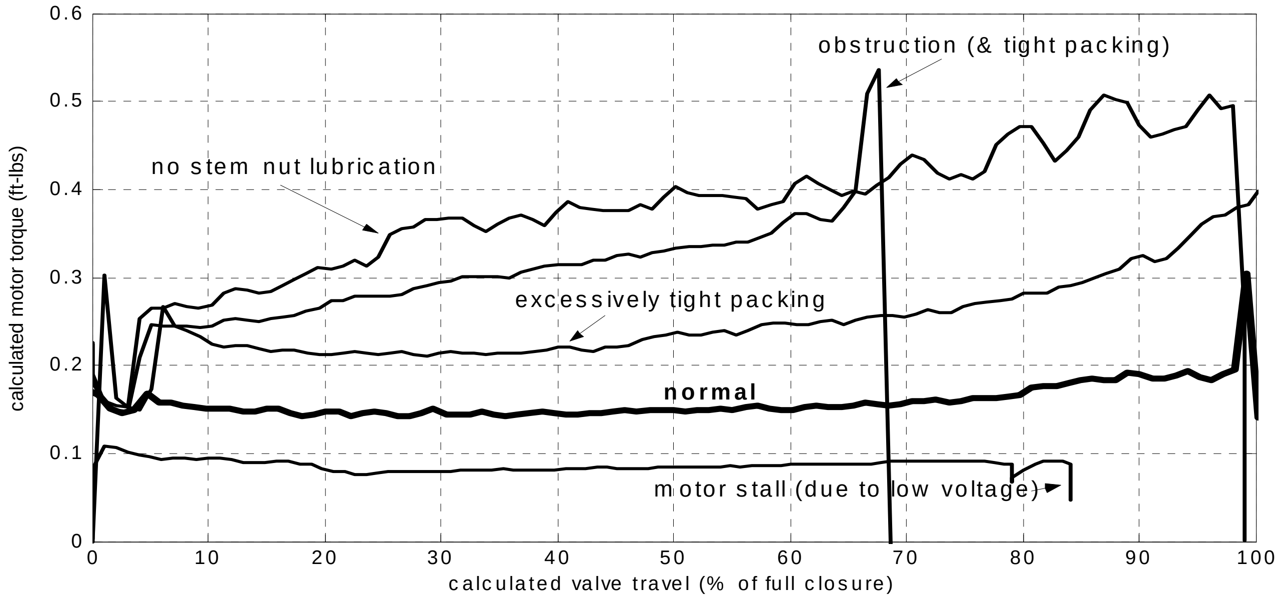


Figure 1. Torque vs. travel signatures for different faults on MOV in flow loop

Repeat steps 1-5 around *twice* the nominal pinion mesh frequency:

- new BP filter settings = 2 x old settings (with max. upper cutoff set to Nyquist freq.)
- increase max. AR model order to twice that used for fundamental, and save resulting autospectrum of AR coeffs. in H_1.

B) Using the two AR spectra, H_0 and H_1, form a weighted composite spectrum, H, by multiplying them together, and then applying a frequency dependent *weighting factor*.

C) Find max. value in H (= H_{max}) and its location - the estimated pinion mesh frequency. Also, store max. value for use in Step E below.

D) Repeat Steps A-C for next time segment, until end of data record is reached.

E) Decide if the estimated pinion mesh frequencies are "valid," by comparing the *amplitudes* of the peaks in the weighted composite spectrum to a time-dependent threshold:

- threshold is determined from a moving average of the max. values determined in Step C.
- if an individual peak value falls below the threshold, assume gear has stopped rotating.

F) Using gear ratios and stem lead, integrate the sequence of pinion mesh frequencies with respect to time, in order to obtain valve position vs. time. Integration is not performed at those times when the peak value of pinion mesh amplitude falls below the threshold determined in Step E.

Fig. 2(a): On/Off run on dyno

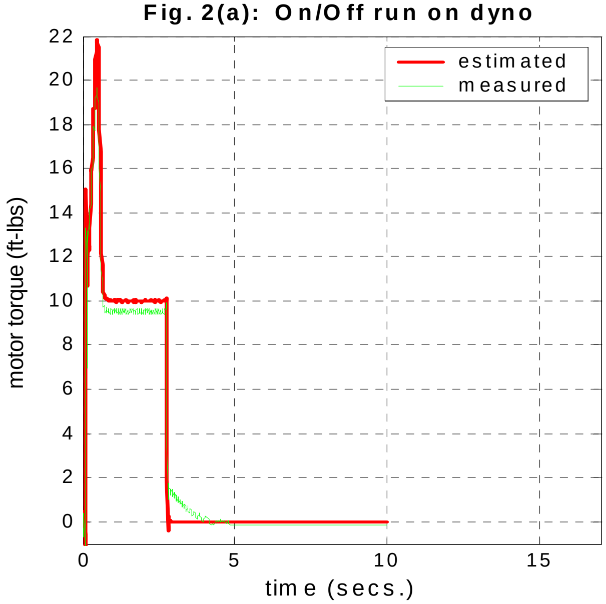
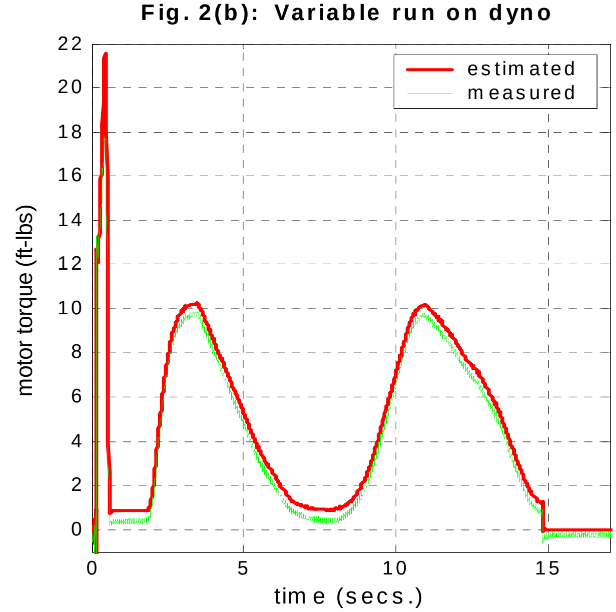


Fig. 2(b): Variable run on dyno



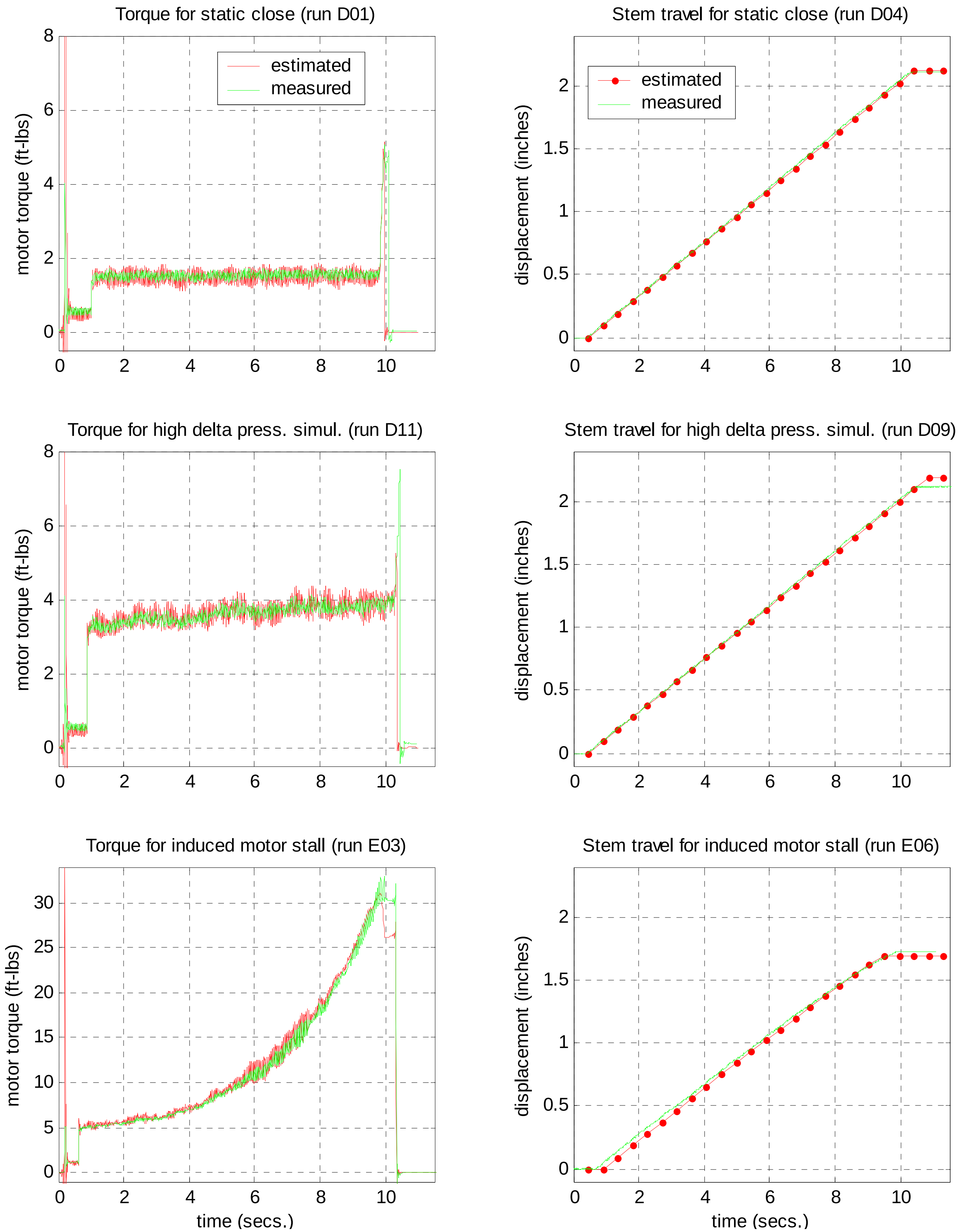


Figure 3. Performance of torque estimator and valve travel routine on MOV at INEEL

Fig. 4(a): Calculated torque for run 14 on Rotork MOV

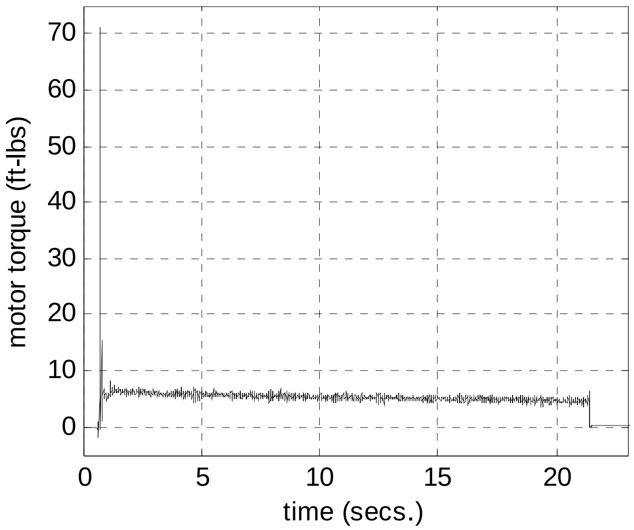
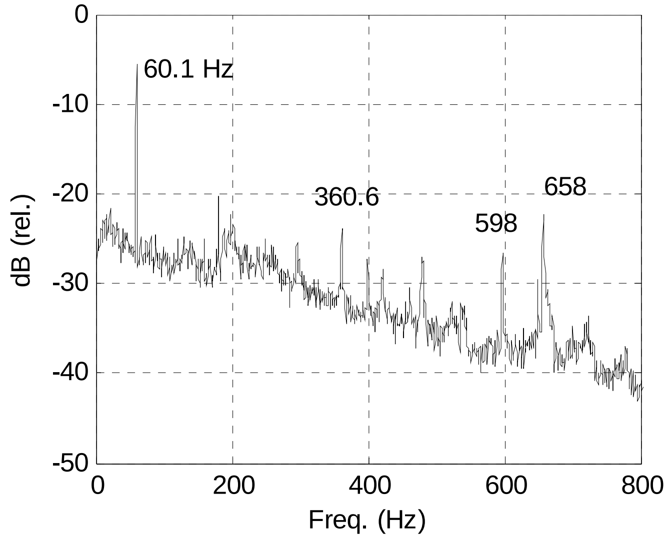


Fig. 4(b): Vibration spectrum for run 14 on Rotork MOV



System Performance

The performance of the MOV diagnostic system has been evaluated using data obtained during four different field tests. These included (1) initial testing of the torque and valve travel routines using an instrumented MOV installed in a flow loop, (2) tests of a prototype system using a motor dynamometer, (3) full-scale "calibration" tests of the system at the Idaho National Engineering and Environmental Laboratory (INEEL), and (4) demonstrations and data gathering sessions during in-service conditions at two different plants.

The initial testing utilized an instrumented Limitorque® SMB-000 MOV with a 3 inch gate valve, which was connected to a flow loop. Flow rates were varied from 0 to 1330 gpm, with electrical, vibration, actuator torque and valve position data collected during closing strokes under the following operating conditions: normal (no degradations), excessive packing compression, motor stall, no stem nut lubrication, and obstruction in valve path. As can be seen in Figure 1, the torque vs. valve travel signatures obtained from these flow loop tests can be used to distinguish between the various faults that were introduced. The results from these tests indicated that the presence of flow was not detrimental to the vibration-based valve travel procedure, and that the methods for estimating motor torque using voltage and current signals were sufficiently accurate to follow the general trend of the measured actuator torques. However, an "offset" or "bias" seemed to exist between the calculated and measured torques. The cause of this offset was identified during subsequent investigation, and was corrected by a combination of using voltage transformers (needed in the data-acquistion chain) with higher phase accuracy, and by modifications to the torque estimation algorithm that decreased the sensitivity of the output to the value of the "forgetting factor" used.

Figure 2 shows comparisons between directly measured motor shaft torques obtained from a motor connected to a dynamometer, and the torques calculated from the electrical signals using the modified version of the torque routines. Results are shown for two different types of loads. For comparison purposes, both the estimated and measured torque signals shown in the plots have been lowpass filtered at 45 Hz, in order to suppress any line frequency components. The measured shaft torques are slightly lower than the calculated torques at the motor air gap, as would be expected if there were any "downstream" motor losses not accounted for in the model assumed by the torque estimator (i.e., other than resistive losses in the windings).

After some further revisions were made to the torque and valve travel routines, the next set of evaluations involved field testing of the system in the MOV lab at INEEL, where the system was used to gather data on a Limitorque® SMB-0 under various configurations and loading profiles. The facility at INEEL does not use a flow loop, but includes an instrumented motor and operator, with the valve stem attached to a load simulator.

Two different valve stems (with different stem leads) were used during the tests at INEEL, with motor pinion/helical gear ratios of 37/35 and 25/47. Data was collected under the following conditions, all at two different torque switch settings: (1) no load (i.e., a static stroke), (2) low load, to simulate a “normal” closing, (3) high load, to simulate overly tight packing or no stem nut lubrication, (4) low differential pressure simulation, and (5) high differential pressure simulation. In addition, for one case the load was increased enough to induce motor stall (with the torque switch bypassed). The rated starting and stall torques for this motor were 25 and 29 ft-lbs, respectively.

Figure 3 compares the calculated and directly measured motor torques and stem travels for some example runs at INEEL. The "D" runs in the Figure used the 25/47 gear set, while the "E" runs used the 37/35 set. Although motor temperature varied throughout these tests, the stator resistance parameter was kept constant at 4.35 Ω.

The torque results from the INEEL tests, as well as from the motor dynamometer tests, indicate that the present version of the motor torque routine is capable of producing estimates

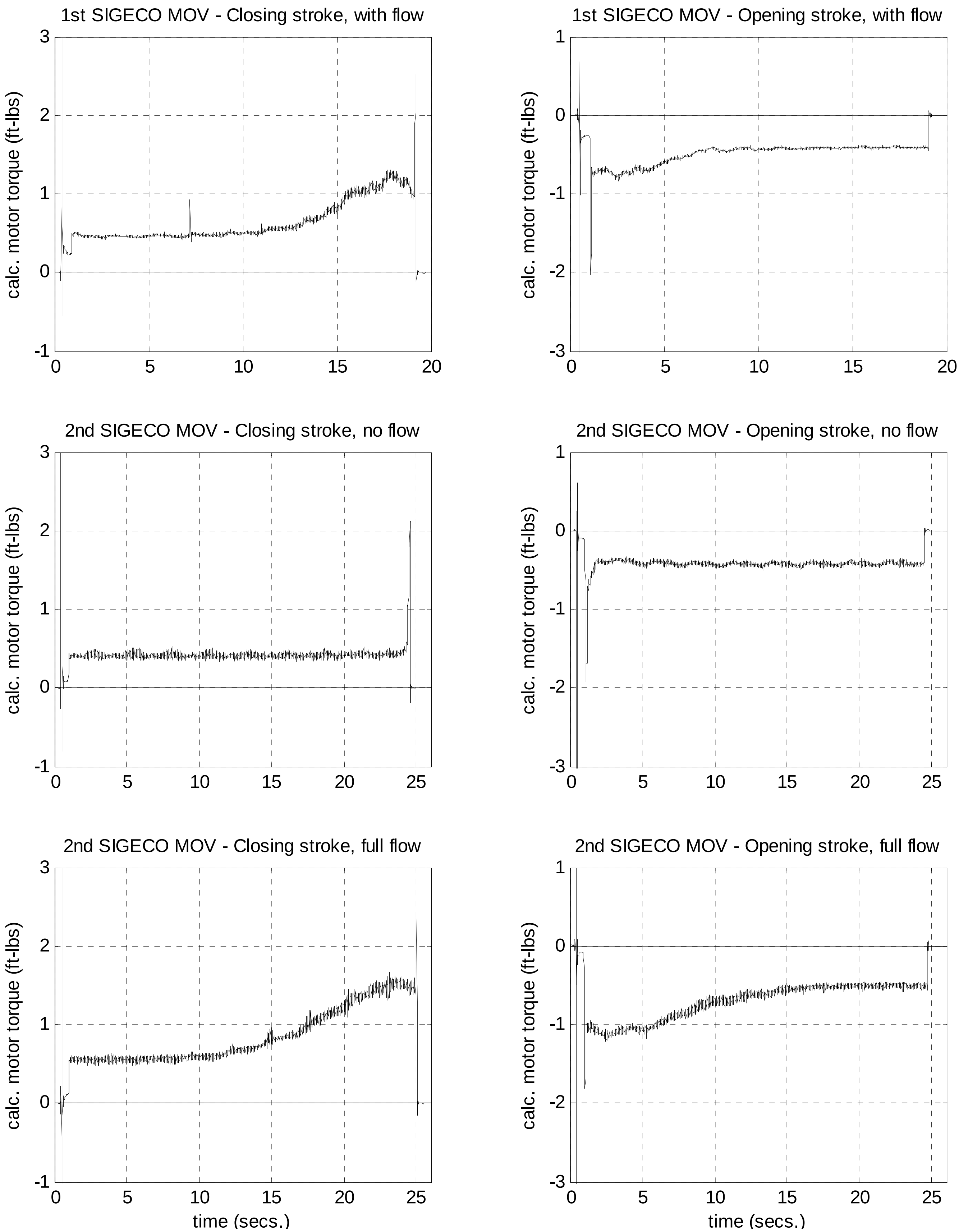


Figure 5(a). Calculated motor torques on two MOVs at Southern Indiana power plant

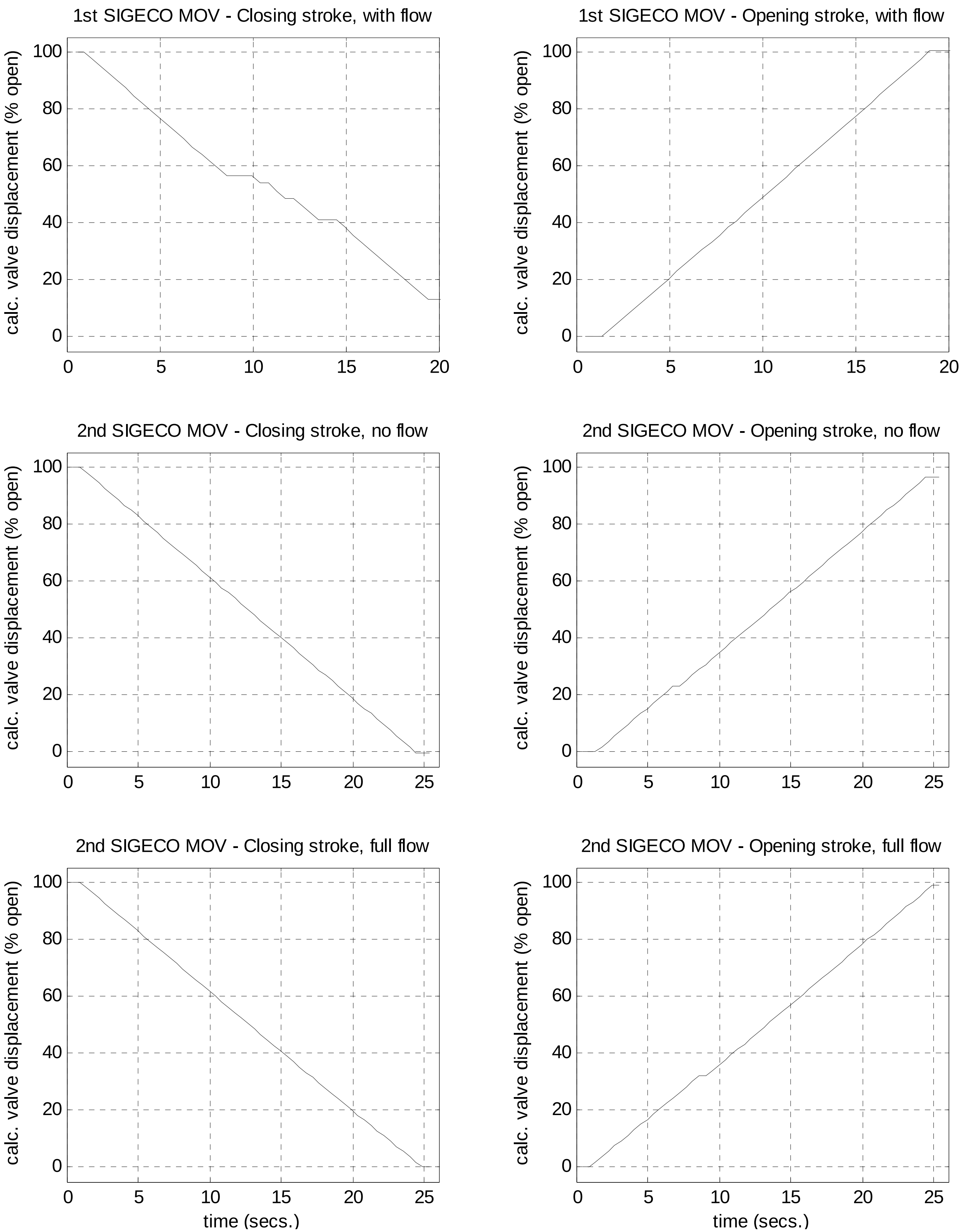


Figure 5(b). Calculated valve travels on two MOVs at Southern Indiana power plant

of fairly high accuracy both in terms of static and dynamic components. In fact, the small-scale oscillations present in the motor torque signals are not "noise", but are modulations of the torque due to motor rotation and worm mesh (there is even some evidence of stem nut rotation as well).

The valve travel estimates track the measured displacements fairly well, although a slight "offset" can sometimes be present. The limited time resolution associated with the valve travel estimates (position estimates are provided approximately every 0.45 secs.) can lead to a time offset, while too low of a "threshold" value (used for accepting or rejecting an estimated pinion mesh frequency, and thereby deciding whether or not the valve has stopped moving - see Step "E" of the valve travel algorithm) can lead to an amplitude offset or to extra calculated travel. It may be possible that one of the electrical signals could be used to bypass most of the functions that the threshold procedure is currently called upon to perform. Or, if the final "diagnostic signature" is presented as motor torque vs. valve travel, then any extra calculated travel at the end of the stroke is less relevant since the motor torque curve itself, in effect, would reveal when the valve has stopped moving. The two results presented separately here since this allows for independent evaluation of the two procedures.

The next set of evaluations, after revisions were made according to the results obtained with the INEEL data, involved taking the system into actual plant environments so that it could be demonstrated and used in collecting data from MOVs under typical operating conditions.

The first plant visited was a local wastewater treatment facility, where we were able to acquire data on a motor-operated gate valve manufactured by Rotork®. This MOV was attached to a 30" diameter pipe, partially filled with a non-flowing liquid. Unlike a Limitorque® actuator, the Rotork® actuator drives the worm gear directly by means of a worm cut into the end of the motor shaft (e.g., there is no motor pinion/helical gear set present). Figure 4(a) shows the motor torque signal calculated using voltage and current data acquired during the last part of a closing stroke on this MOV. Due to the nature of this type of MOV, there is no "seating" torque at the end of the stroke (the motor just shuts off when the valve is near the end of its stroke). There is, however, a "hammer blow" like effect visible near the beginning of the stroke. Although a direct measurement of torque was not available, we can compare the calculated motor torque to the rated torque given on the nameplate, which in this case states the maximum output of the actuator as 750 ft-lbs. Dividing this figure by the overall gear ratio of 60:1 gives us an approximate maximum motor torque of 13 ft-lbs, which compares favorably with the calculated running torque of about 6 ft-lbs during this (unloaded) stroke.

Since there is no pinion/helical gear set in the Rotork® actuator to produce pinion mesh vibration, we would have to look for the lower frequency worm gear mesh (or its harmonics) if we were to try to obtain an estimate of valve travel from the vibration data. The valve travel routines are not presently set up to handle this situation, since they were customized assuming a Limitorqe® type of MOV. However, the spectrum of the measured acceleration signal, shown in Fig. 4(b), reveals a strong component occurring slightly below the line frequency of 60.4 Hz in this plant. If confirmed to be due to worm mesh (since the actual motor speed in this case is unknown, we cannot be sure this component is in fact due to worm mesh), this component could be tracked in a manner similar to that employed in the present algorithm for tracking pinion mesh. Or, it may be possible to obtain valve travel more readily in this case using the calculated motor torque signal, which contains other, as yet unidentified, spectral components.

The next in-plant test took place at the Southern Indiana Gas and Electric Company's (SIGECO) Culley station, a coal-fired power plant near Evansville. During this visit, data was collected on two different Limitorque® MOVs. Both of these valves serviced high pressure (1200 psi), small diameter (approx. 1.5 in.) steam lines, and, for one of them, we were able to control the maximum flow via a hand valve immediately upstream of the MOV. Both motors ran off of line voltages of 480 VAC, at nominal speeds of 1800 rpm. The first MOV (denoted "main steam lead drain") was a gate valve with an L120-10 operator, and had the following parameters: 19 teeth on motor pinion gear, 33 teeth on helical worm shaft gear, 33 worm gear teeth, and measured per phase winding resistance of 29 Ω. The second MOV (denoted "main stop valve above seat drain") was a globe valve with an SMB type of operator, and had the following parameters: 15 teeth on motor pinion gear, 26 teeth on helical worm shaft gear, 46 worm gear teeth, and per phase inding resistance of 29 Ω.

Some examples of calculated motor torques obtained during the opening and closing strokes for the two SIGECO MOVs are shown in Figure 5(a). The top two plots in this figure show results from the first valve (with flow), while the lower four plots show motor torques for the second MOV, with and without flow. The valve travel results for these same conditions are shown in Figure 5(b), with displacement plotted as a percentage of full stroke. Features such as hammer blow, valve seating, drive sleeve engagement near the start of closure, the increase in motor torque associated with increased flow, and motor power on/off points are all discernible in the motor torque curves.

For the most part the travel estimates look reasonable, starting and stopping at the expected points. However, they are somewhat erratic for the closing stroke in the first MOV, but this may be because for this valve the magnetically-mounted accelerometer had to be attached to the motor itself, due to the normal mounting point on the operator being cast aluminum. A point down on the valve yoke was also tried on this first MOV, but the gear mesh vibration at this location was too weak to be useful. Glitches in the calculated valve travels during the opening strokes of the second MOV (visible as a "step" in the middle of these plots) reflect times when the calculated pinion mesh amplitudes fell below the threshold used for determining whether or not the valve had stopped rotating. As mentioned above, there are several strategies available which could prevent such glitches from occurring, but these have not yet been implemented or tested. Of course, the threshold can be optimized for any particular MOV, but our objective is to use a universal parameter to govern the calculation of this threshold, rather than to require any user input The parameter chosen is the best compromise based on all the MOV vibration data that has been available to us during this program.

Description of a Prototype System

A prototype portable system for performing non-invasive, in-service monitoring of motor operated valves has been built and tested. This system uses a combination of electrical voltage and current measured at the motor control center to determine the instantaneous motor torque, and vibration measured on the operator casing to determine valve position. Both these quantities can be displayed separately as a function of stroke time, or they can be combined into a single "diagnostic signal" as motor torque vs. valve position. The hardware in the system consists of a portable industrial PC with data acquisition and filtering cards, an I/O box, and various signal condition equipment (current probes, voltage leads and transformer module, magnetically mounted industrial accelerometer and power supply, and cables). The custom software consists of routines that implement our motor torque and valve travel algorithms, along with a graphical user interface that controls various aspects of setup, signal acquisition, display of results, and data archiving. For motor torque estimation, the user has only to supply the per-phase winding resistance of the motor under test, while for valve travel, the user supplies information about gear ratios and the valve stem lead.

Summary

A portable system for non-invasive, in-service monitoring of motor operated valves has been built, tested, and then demonstrated in plant environments. This system uses a combination of electrical voltage and current measured at the motor control center to determine the instantaneous motor torque, and vibration measured on the operator casing to determine the position of the valve.

The results obtained after applying the present version of the torque estimator to a range of different motors and conditions all indicate that this procedure is able to accurately track the torques actually delivered by these motors, both in terms of their static and dynamic components. The present version of the valve travel algorithm yields valve position estimates that are very much in line with measured and expected results over a range of MOVs and conditions, although there are occasions when "steps" or extra position estimates can be added. The former occurs if the pinion mesh tracking routine produces an amplitude "threshold" that is too high, while the latter occurs if it is set too low. Several options for avoiding or reducing such occurrences are available, including doing away with the threshold by relying instead on one of the electrical signals to decide whether or not the valve has stopped moving.

We have also seen that the calculated motor torque signals contain information regarding motor rotation rate and worm mesh, thus making it possible that valve travel itself could be extracted from the motor torque signal with a similar or perhaps even higher degree of accuracy than is currently obtained using the vibration signal. There is also evidence of the very low frequency stem nut rotation rate showing up in the calculated motor torque signal, which has the potential to reveal the condition of this part of an MOV. However, rather than determining the "strength" of the stem nut rotation component by trying to detect and monitor its amplitude in this noisy portion of the frequency domain, a procedure was developed that utilizes the power cepstrum of the calculated motor torque signal to enhance the detection of this component. Tests of this procedure using electrical data from an MOV with and without a stem nut fault indicate that it is better able to reveal the presence of such a fault than methods based on spectral energy density or amplitude alone.

References

1. "The Electromechanical Monitoring of Motor-Operated Valves - Final Report", W.H. Hagman, J.H. Lang and R.H. Lyon, Massachusetts Institute of Technology, Laboratory for Electromagnetic and Electronic Systems Technical Report TR95-004, June 23, 1995.

2. "In-Service Diagnostics of Motor Operated Valves: Results of Flow Loop Testing", D.L. Bowen, K. Herbert, R.H. Lyon, RH Lyon Corp Report 96-001 to the NRC, January 5, 1996.

3. "Non-Invasive Recovery of Gear Rotation from Machine Vibration", C.A. Lerch, S.M. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, February, 1995.