Conf-890555--

CONDITION MONITORING OF MACHINERY USING MOTOR CURRENT SIGNATURE ANALYSIS*

CONF-890555--3

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To be presented at the
Seventh Power Plant Dynamics, Control and Testing Symposium
Knoxville, Tennessee
May 15-17, 1989

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*Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, under Interagency Agreement DOE 1886-8082-8B with the U.S. Department of Energy under Contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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SUMMARY

Motor current signature analysis (MCSA) is a powerful monitoring tool for motor-driven equipment that provides a nonintrusive means for detecting the presence of mechanical and electrical abnormalities in the motor and the driven equipment, including altered conditions in the process "downstream" of the motor-driven equipment. It was developed at the Oak Ridge National Laboratory as a means for determining the effects of aging and service wear specifically on motor-operated valves used in nuclear power plant safety systems, but it is applicable to a broad range of machinery.

MCSA is based on the recognition that an electric motor (ac or dc) driving a mechanical load acts as an efficient and permanently available transducer by sensing mechanical load variations, large and small, long-term and rapid, and converting them into variations in the induced current generated in the motor windings. These motor current variations are carried by the electrical cables powering the motor and can be extracted at any convenient location and processed as desired. Motor current signatures, obtained in both time and frequency domains, provide equipment condition indicators that may be trended over time to provide early indication of degradation.

Successful applications of MCSA technology (patent applied for) include not only motor-operated valves but also pumps of various designs, blowers, and air conditioning systems. Examples are presented briefly, and speculation regarding the applicability of MCSA to a broader range of equipment monitoring and production line testing is also given.

1. BACKGROUND

In support of the NRC-funded Nuclear Plant Aging Research Program, Oak Ridge National Laboratory (ORNL) recently completed a comprehensive assessment of the aging of motor-operated valves (MOVs). In addition to studying the recorded operating histories of the large number of these devices found in nuclear power stations, a primary objective of the study was to identify and assess the effectiveness of diagnostic techniques and equipment with which to determine the operational readiness of MOVs, that is, their ability to perform

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their design function on command (especially under accident conditions). In carrying out this assessment, many MOV electrical signals and mechanical and thermal parameters were recorded and examined for their information content relative to aging phenomena. One such signal, the instantaneous fluctuations (noise) in the electric motor current flowing through the power leads, stands out from the others in terms of the richness of its information content and the simplicity with which it can be acquired and analyzed.

As a result of extensive laboratory and field investigations carried out by ORNL, it was discovered that motor current signatures—representations in both time and frequency domains—provide very sensitive diagnostic indicators of the condition of both the valve and its motor-driven operator. The means by which "trendable" parameters are extracted from the raw motor current signal and related to physical processes, including degradation, has been termed "motor current signature analysis" (MCSA).

2. OPERATING PRINCIPLES

2.1 DATA ACQUISITION METHODOLOGY

As illustrated in Fig. 1, motor current signals can be obtained remotely (typically at a motor control center, which may be several hundred feet from the equipment to be monitored) and noninvasively by means of a single split-jaw current probe placed on one of the power leads. (Because no electrical connections need to be made or broken, shock hazard is minimal.) The resulting raw current signal is amplified, filtered, and further processed as appropriate to provide a sensitive and selective means for extracting motor current noise information that reflects instantaneous load variations within the drive train and the ultimate load.

Two separate diagnostic signals are developed from the single probe input: one optimized for time-domain analysis using a waveform recorder and the other optimized for frequency-domain analysis using a Fourier transform (spectrum) analyzer. Although the details of the signal conditioning embodied in the custom electronics package are proprietary, the basic objective of the optimization is maintenance of dynamic range in the subsequent data analysis processes. This is accomplished by eliminating those portions of the signal that lend nothing to the analysis process employed. For field use, it is convenient to combine the two analysis instruments shown separated in Fig. 1 into a single unit by emulating their functions on a personal computer equipped with special hardware and software (Fig. 2). The data shown throughout this paper were acquired using the portable setup shown.

2.2 MOTOR OPERATOR BASICS

Since the discussions that follow require a basic understanding of how a motor operator performs its function of actuating a valve, a brief tutorial of the Limitorque electric motor-driven operator is now presented. Figure 3 shows the location of major switches and drive train elements that play key roles in later discussions.

When energized, the drive motor, operating through a single stage of gear reduction, turns a worm shaft at reduced speed. A worm, which is splined to

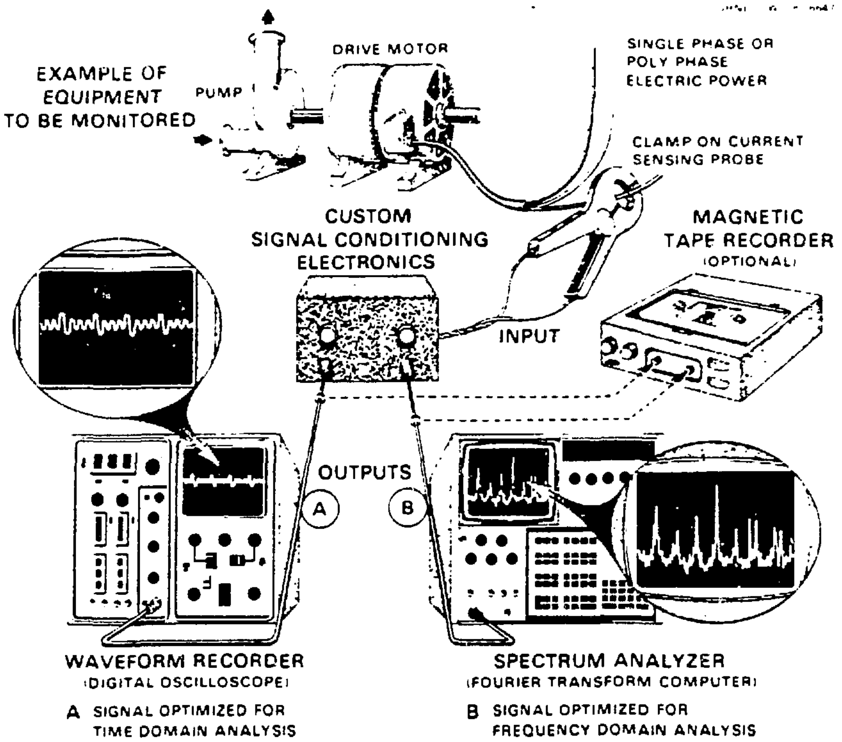

Fig. 1. Artist's illustration of the manner in which MCSA is typically applied to motor-driven equipment—in this case, a centrifugal pump.

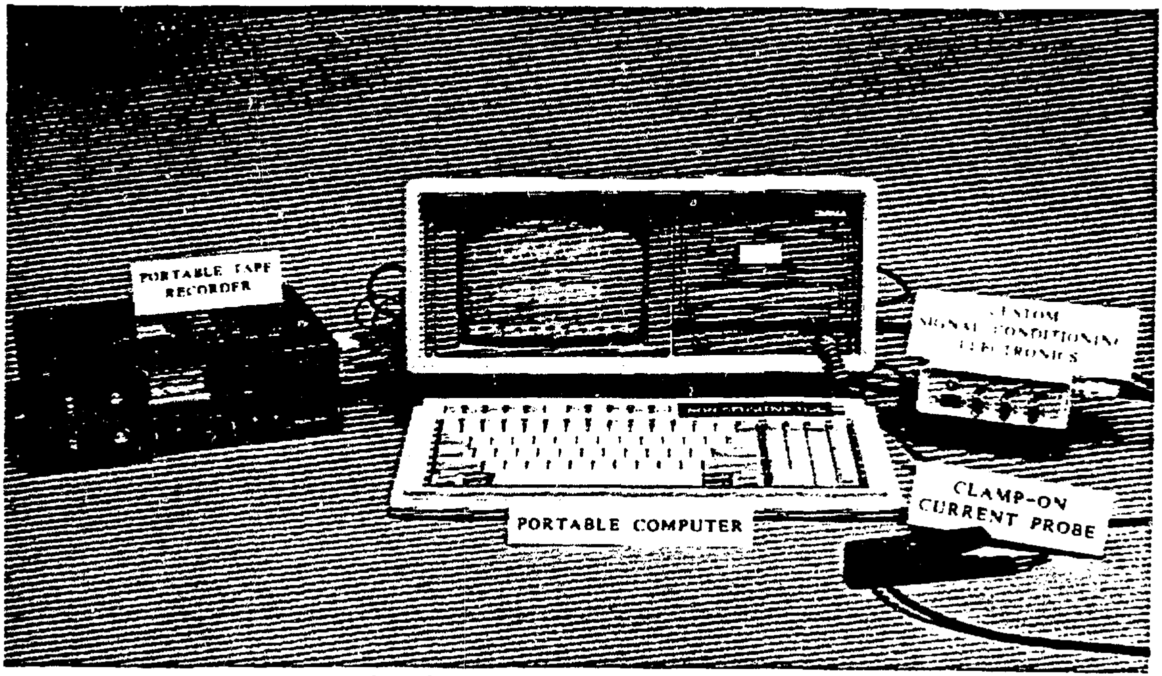

Fig. 2. Photograph of an MCSA system suitable for laboratory or light-duty industrial use. The portable computer is outfitted with special hardware and software to enable it to perform as both a waveform recorder and a spectrum analyzer.

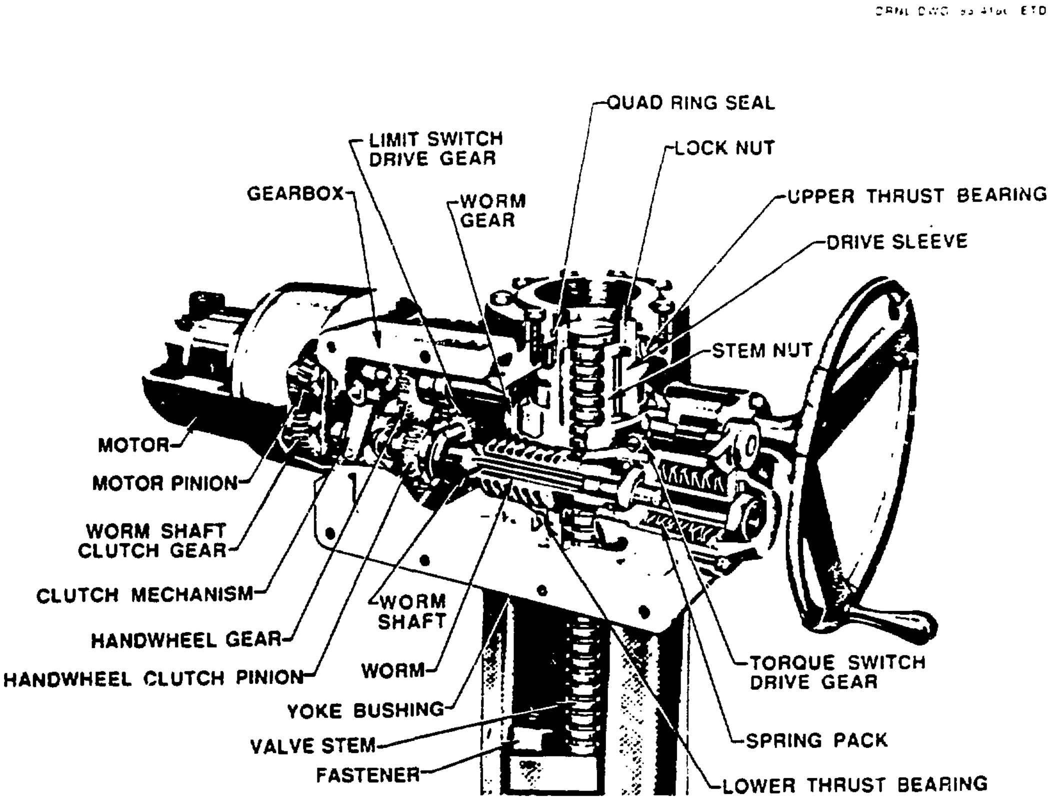

Fig. 3. Cutaway view of an electric motor-driven operator connected to a rising-stem valve (not shown).

the worm shaft, rotates with the shaft and drives the worm gear about an axis perpendicular to the worm shaft. The worm gear is equipped with two drive lugs that can contact two similar lugs on the drive sleeve. Since the lugs are spaced 180° apart, as much as one-half rotation of the worm gear can occur before the two sets of lugs engage and thereby initiate rotation of the drive sleeve. This lug engagement results in a "hammerblow" effect within the operator, which serves two purposes: (1) it allows the motor and drive train to attain full speed before being significantly loaded, and (2) it provides a sudden impulse of large magnitude with which to overcome the stored energy and static friction forces present in a valve that has been closed hard against its seat.

The stem nut is splined to fit inside and rotate with the drive sleeve. It is generally threaded internally to mate with the thread of a rising valve stem such as that used in gate and globe valves.

The torque transferred by the worm to the worm gear results in a reaction force that pushes the worm axially along the worm shaft splines and thus compresses a spring pack consisting of a stack of Belleville washers. The amount of axial worm movement is proportional to the worm gear forces and hence, for a spring pack which obeys Hooke's Law, provides a rough measure of the amount of stem thrust delivered by the motor operator. Capitalizing on this relationship, a rack and pinion is usually provided to convert the linear movement of the worm into a corresponding rotation of a "torque switch," whose function is to remove electrical power from the motor by opening its contacts when a preset angular rotation (representing a preset torque condition) has been reached.

A second ("limit") switch is geared directly to the worm shaft (or, in some models, to the drive sleeve) so as to count rotations of the shaft during MOV operation. This switch, arranged to open (or close) its contacts at the occurrence of a preset number of worm shaft (or drive sleeve) rotations, is generally utilized to stop the motor operator at the end of the valve stroke and/or to illuminate or extinguish valve position indicator lamps at the control panel.

The wiring configuration for the torque and limit switches is determined by the user, but ordinarily the torque switch is wired to interrupt power to the motor at the desired point of valve closure and the limit switch is wired to stop the motor at the full-open valve position.

2.3 COMPARISON OF MOTOR CURRENT AND ACCELEROMETER SIGNALS

Appreciation for the fact that an electric motor acts as an effective transducer for load variations both within itself (windage, bearing friction) and downstream (in the drive train and in the device driven) may be gained by comparing a motor current signature with data acquired from an accelerometer mounted on the same machine (see Fig. 4), in this case a valve operator powered by an 1800-rpm three-phase induction motor. Those experienced in vibration analysis and familiar with the construction of gear-driven valve operators will not be surprised to see pronounced peaks in the accelerometer signal spectrum (lower half of the figure) at frequencies corresponding to the motor speed (slightly less than 30 Hz) and at the worm gear tooth meshing (WGTM) frequency (15.5 Hz) and its harmonics. These same signal components appear prominently in the motor current spectrum (upper half of the figure), although the amplitude relationships are different.

The two spectra also show some distinct differences. Among these is the appearance of a strong spectral component in the motor current signature at about 1.5 Hz, identified in Fig. 4 as the slip frequency, for which there is no corresponding peak in the vibration signature. This signal component is a general characteristic of ac induction motors and reflects the rate at which the spinning armature continually falls behind the rotating electrical field generated by the motor's field windings. Since this motor slip frequency component is electrical rather than mechanical in origin, it has no vibrational counterpart. Another obvious difference in the signatures is the appearance of a sharp peak at about 14.3 Hz in the accelerometer's spectrum that is not reflected in the motor current signal. Precise measurement of its frequency proves that this peak is <u>not</u> the first subharmonic of the motor rotational speed. Moreover, examination of accelerometer spectra obtained from structural impact tests performed with the operator inactive shows that the 14.3-Hz peak is not a preferred vibrational mode of the massive valve operator itself. While its mechanical origin remains a mystery, it would seem that very little energy from the electric motor is required to sustain this oscillation, otherwise a corresponding peak would be present in the motor current spectrum.

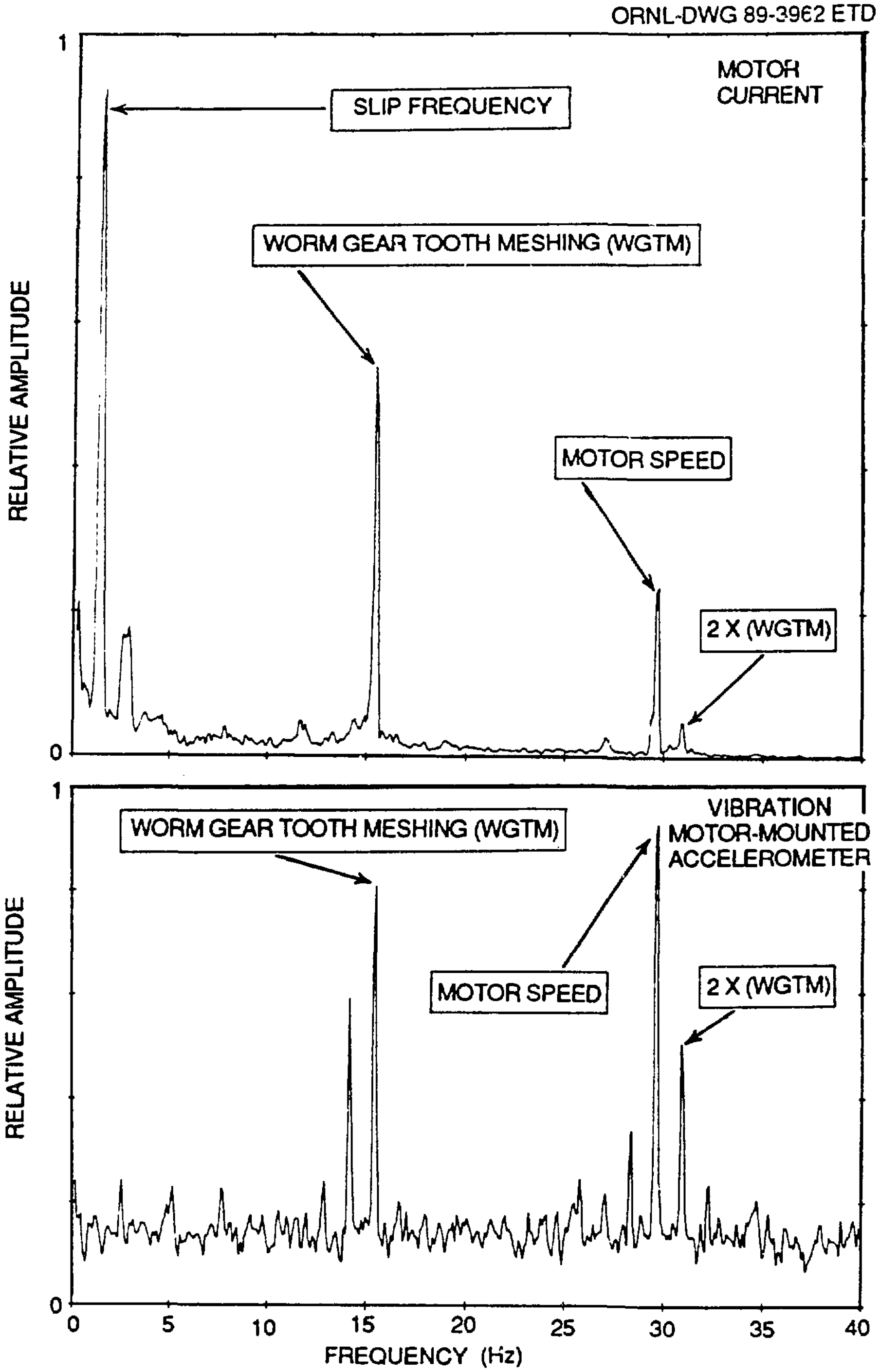

Fig. 4. A comparison of motor current and mechanical vibration spectra acquired simultaneously on an MOV.

3. CONDITION INDICATION OF MOVs

MCSA performed by ORNL on both healthy and degraded motor-operated valves has demonstrated a capability to indicate the internal condition and performance of these devices with both high sensitivity and selectivity. The major condition-indicating features that are extractable from the motor current time signature (waveform) are

- average running current values during selected time segments of valve operation (e.g., no-load, pre-unseating, and midstroke);
- pronounced variations (maximum and minimum currents, general appearance of time trace) associated with changes in mechanical load during a valve stroke;
- initiation time, duration, and magnitude of transient events (e.g., operator hammerblow; valve unseating, seating, and backseating; unexpected transients resulting from valve obstructions, damaged gear teeth, or damaged stem threads); and
- worm gear tooth meshing on a tooth-by-tooth basis.

The major condition-indicating features that are extractable from the motor current frequency signature (spectrum) are

- overall level of current noise (generally indicative of smooth or rough operation);
- spectral peaks resulting from periodic load variations within the MOV drive train, such as
  - worm gear tooth meshing, stem nut (worm gear) rotation, and motor shaft speed (also observed as motor slip);
  - harmonics of fundamental peaks and sidebands (sum and difference frequencies) surrounding them, whose presence is usually indicative of wear and/or eccentricity;
- spectral peaks and other features commonly encountered in traditional machinery vibration analysis, such as prominent peaks associated with pedestal resonances, imbalance, and bearing problems; and
- relatively broadband spectral energy resulting from flow and pressure fluctuations sometimes observed in pumps.

Many of the signature features described above are illustrated in the next section.

3.1 FEATURES PRESENT IN NORMAL MOVs

Figure 5 shows a motor current waveform obtained from a typical large gate valve powered by a Limitorque operator. The MOV under test was not attached to any piping and contained no process fluid. The upper half of the figure depicts the open-to-closed stroke and the lower half the closed-to-open stroke. Among the features seen in these signatures are the transients

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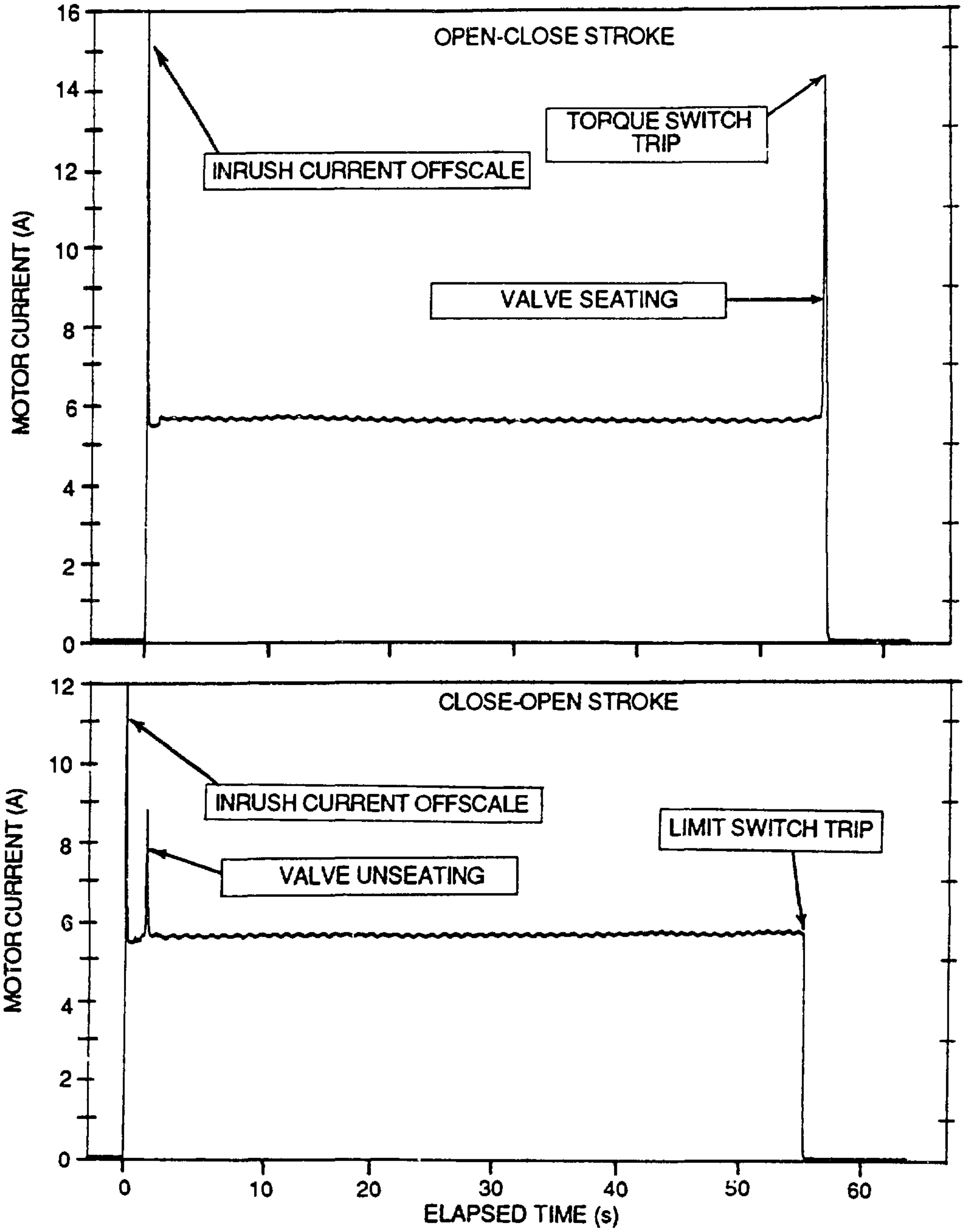

Fig. 5. A typical time-domain motor current signature for a lightly loaded MOV, showing each stroke direction separately.

produced by gate seating and unseating (this valve was set up to close on torque switch trip and to open on limit switch trip). The very large but short-lived inrush current transient marks the time of actuating switch closure. Its peak value, not displayed on the scale of this graph, is not an indicator of valve or operator condition in most circumstances but may provide useful diagnostic information on the motor.

The "rippling" character of the midstroke motor current waveform is seen on a magnified scale in Fig. 6. Because the drive motor for this operator is a 4-pole (nominally 1800-rpm) design, each cycle of the ripple (~1 s) corresponds to the loss of 90° of motor shaft rotation (slip) relative to synchronous rotation with the motor's magnetic field. We note in passing that even though this valve was in good condition, there is indication of a minor valve stem irregularity in both the opening and closing direction waveforms in the time period 8 to 15 s from the open end of the valve stroke. This anomaly was not investigated but may have been due to damaged threads or insufficient stem lubrication along the common segment of the stem that is represented at the opposite ends of the two plots.

Additional detail on the transient phenomena usually observable during an open-to-closed stroke is given in Fig. 7, where the initial and final portions of the upper half of Fig. 5 are displayed on an expanded scale. The load addition caused by packing friction at the beginning of stroke is evident when the stem first moves; prior to that time (about 1 s into the signature) the load imposed on the drive motor is due solely to gear and shaft bearing friction within the valve operator. Any variation in the time of first stem movement could reflect altered clearances between gear teeth or between stem and stem nut threads, or worn lugs on the worm gear or the drive sleeve. Variations in the magnitude of the increase in running current accompanying stem movement could reflect altered packing friction or stem thrust requirements (due, for example, to a change in absolute internal valve pressure). The load addition of 9.14 A at the end of stroke indicates wedging of the gate into its seat. Any roughness of the valve guides or an obstruction in the seating area would be evidenced by departures from the smooth, monotonic current rise occurring during the final 0.6 s prior to torque switch trip of the motor.

Figure 8 shows the first 5 s of the closed-to-open stroke plotted with magnified scales so as to display additional signature features. The prominent peak occurring ~2 s after operator actuation is the result of increased demand for motor torque caused by a need for additional stem thrust (tension) with which to pull the gate from its seat. The lower half of Fig. 8 provides information similar to the upper plot of Fig. 7, except that a new feature is now clearly visible: the hammerblow within the valve operator that is created at the moment the rotating worm gear lugs contact the lugs on the stationary drive sleeve, thereby initiating drive sleeve and stem nut rotation and permitting relief of stem compression. Once again, any variations in the magnitude or the time of initiation of the hammerblow feature would provide an indication of altered mechanical status of the drive train within the operator.

A frequency-domain signature of this same motor operator is given in Fig. 9, with the 32-Hz overall frequency range divided into two intervals for clarity. This spectrum was computed from the steady state portion of the open-to-closed

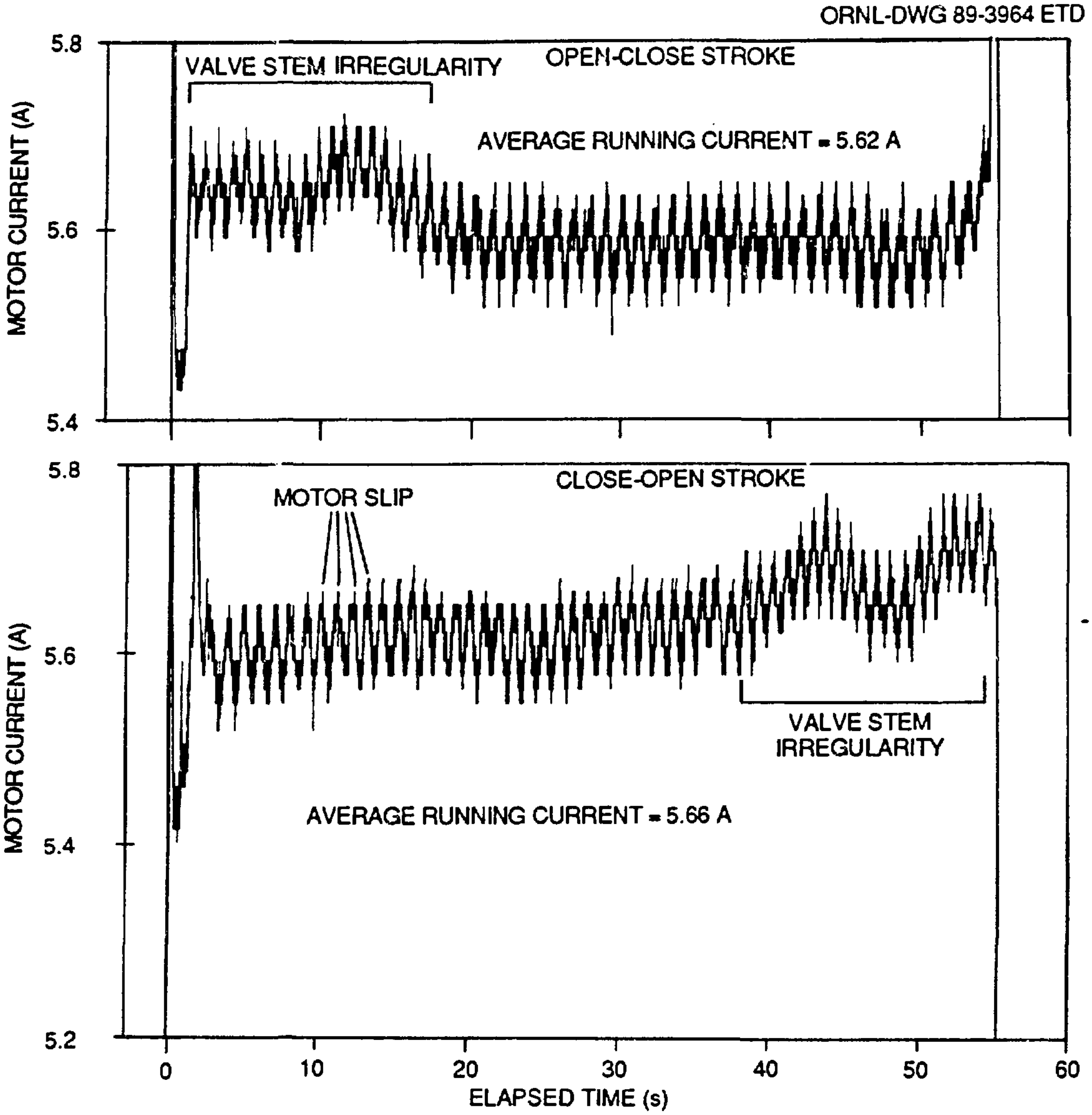

Fig. 6. The midstroke running current portion of Fig. 5, plotted with an expanded vertical scale.

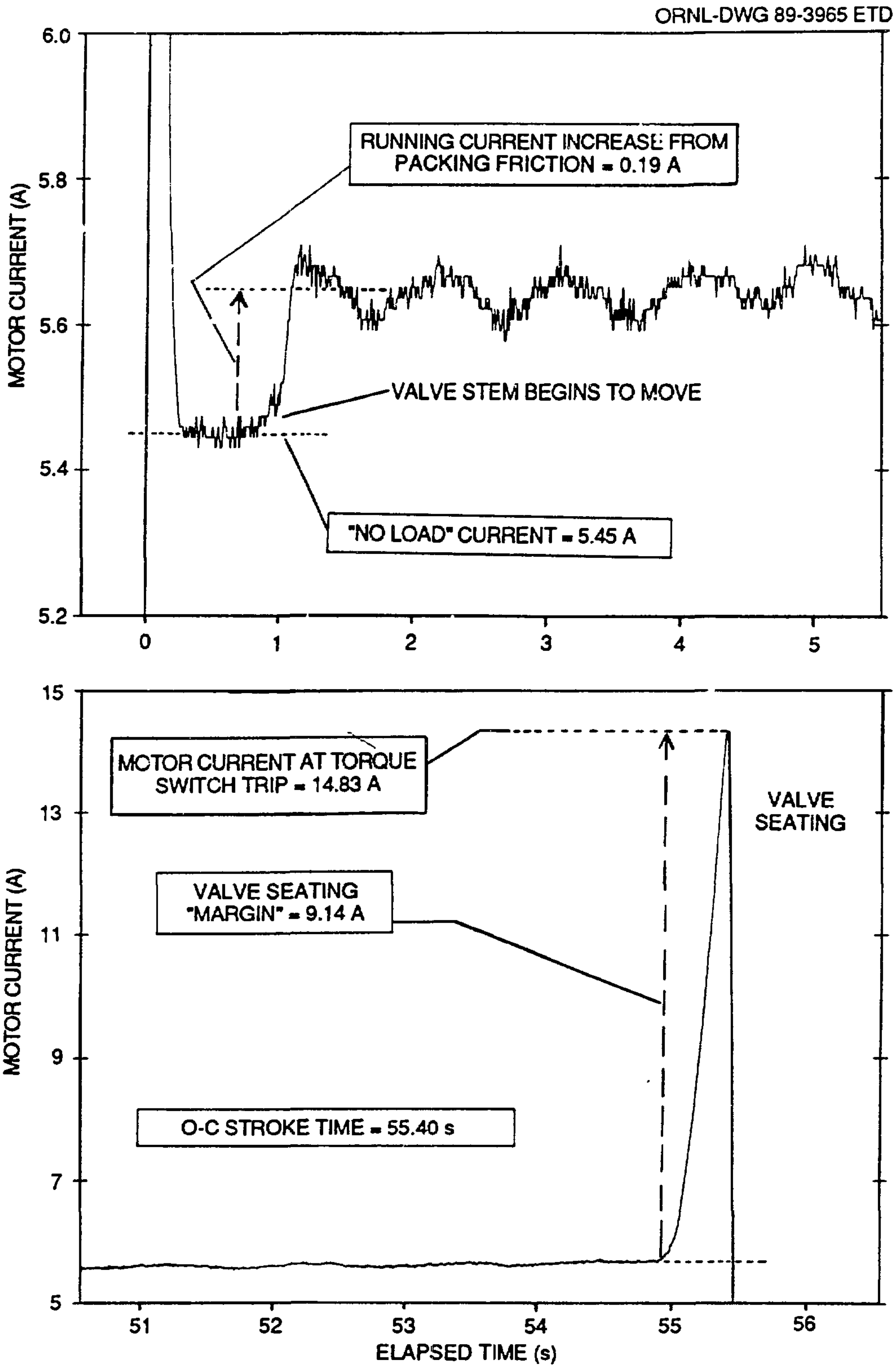

Fig. 7. The initial and final 5 s of the open-to-closed stroke motor current signature, plotted with expanded vertical scales.

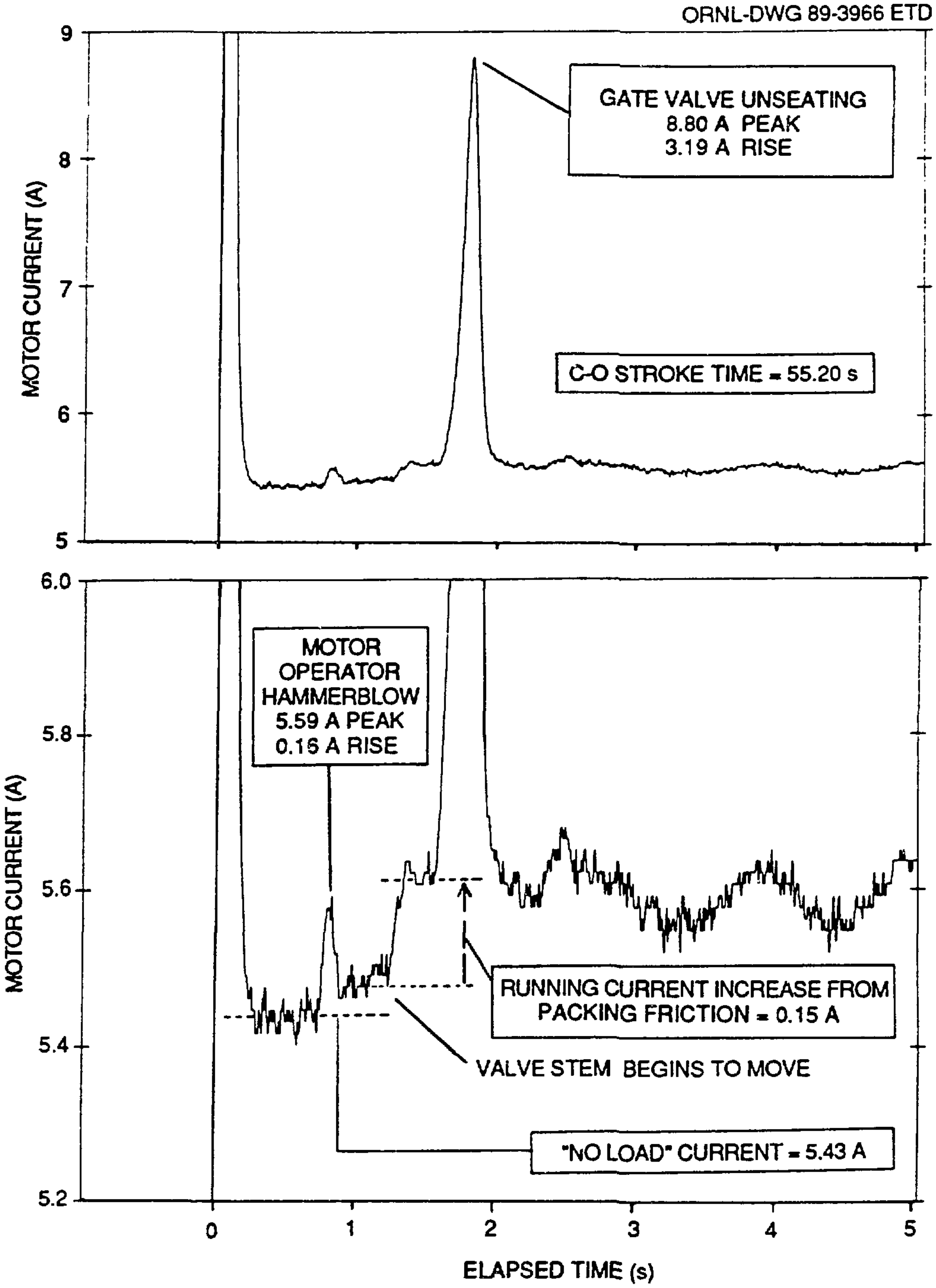

Fig. 8. The initial 5 s of the closed-to-open stroke motor current signature, plotted with two degrees of vertical scale expansion.

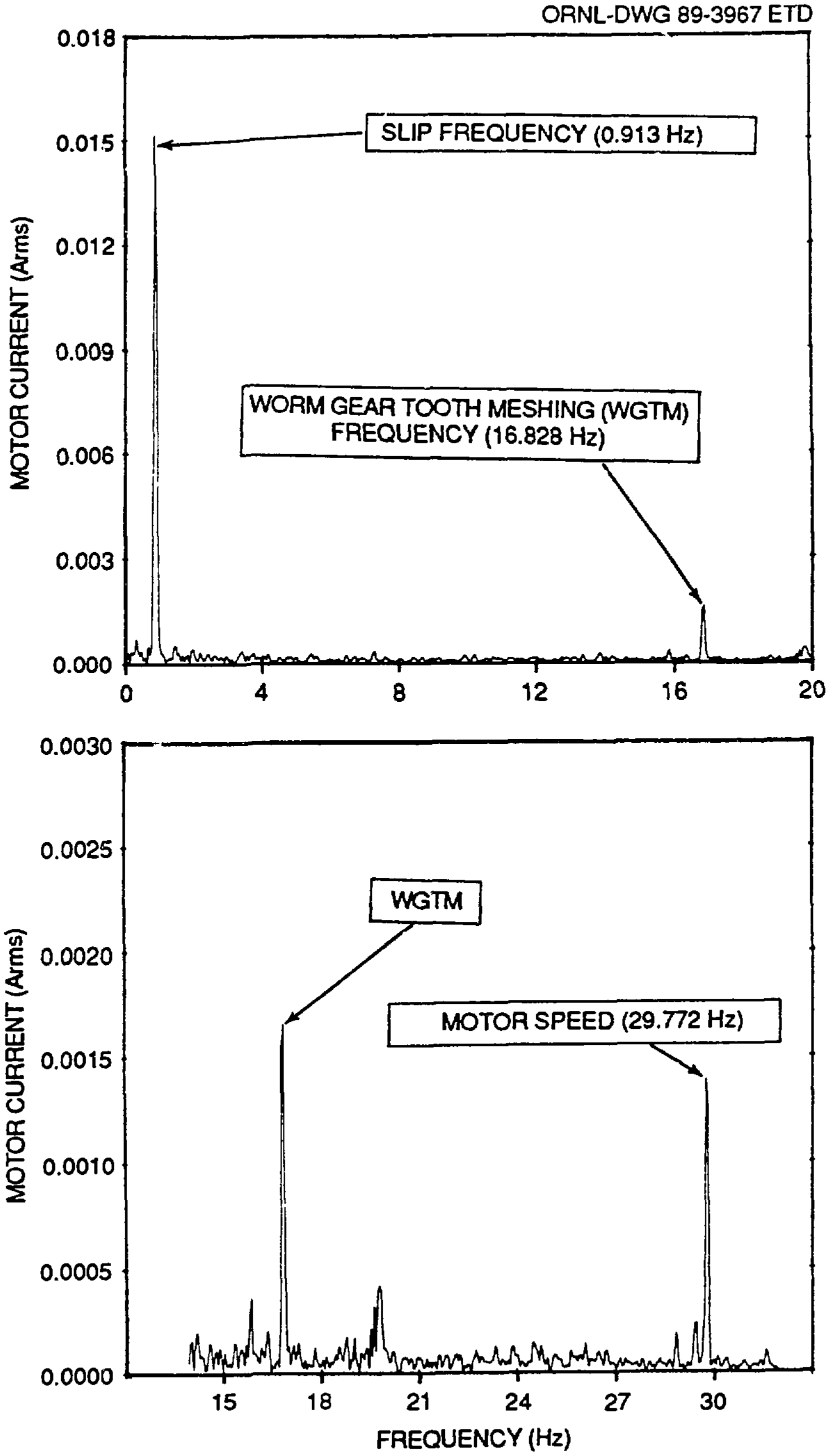

Fig. 9. A frequency-domain motor current signature for the same lightly loaded valve whose time-domain data are shown in Fig. 5. This signature was obtained during the transient-free (midstroke) portion of the open-to-closed stroke.

valve stroke (upper half of Fig. 5), that is, the interval from ~3 to 53 s, which is free from transients. The most prominent feature is the motor slip (frequency = 0.913 Hz) that was also seen to dominate the time traces shown previously. The slip frequency is tied to the actual motor shaft speed (29.772 Hz) by the relation

$$\text{slip frequency} = (\text{synchronous speed} - \text{motor shaft speed}) \times (\text{no. of motor poles}) \tag{1a}$$

or

$$0.913 \approx (30.000 - 29.772) \times (4); \tag{1b}$$

these two spectral peaks are, in fact, different manifestations of the same phenomenon. The second largest peak in the motor current spectrum is caused by WGTM and appears at the frequency of rotation of the worm shaft, as computed from the relation

$$\text{worm shaft rotational frequency} = (\text{motor shaft speed}) \frac{(\text{no. of teeth on motor pinion gear})}{(\text{no. of teeth on worm shaft clutch gear})} \tag{2a}$$

or

$$16.828 = (29.772)\ (26/46) \tag{2b}$$

for this particular MOV. Other, smaller peaks also can be seen in Fig. 9; in some cases they are reproducible from stroke to stroke and thus can be ascribed to a particular physical phenomenon, but in other cases their appearance is apparently random.

This concludes an abbreviated presentation of motor current signature features typical of MOVs operating normally. However, before leaving the subject it should be remarked that, although the results shown were acquired from an ac-powered operator, MCSA methods apply equally well to dc-powered operators as long as the following differences are recognized:

- No slip frequency peak will be present in the frequency spectra for dc-powered machinery, but the motor shaft speed peak will still be available for computing the expected frequencies for downstream shafts and gears.
- Direct-current motors are inherently more sensitive to variations in line voltage and load than ac induction motors; hence, spectral peaks will shift as these parameters change.
- Load-related information can be extracted at much higher frequencies from dc-powered operators, since the 60-Hz carrier frequency demodulation limitation imposed by the ac line is lifted; frequencies as high as 700 Hz (produced by motor pinion gear meshing) are readily observed in MOVs.
- A Hall effect current probe is used in place of a current transformer for sensing the dc current noise.

3.2 DETECTION OF MOV ABNORMALITIES

MOV tests conducted by ORNL have shown MCSA to be capable of detecting, differentiating, and tracking the progress of the following abnormalities:

- stem packing degradation or tightness changes
- incorrect torque switch settings and/or varying switch trip points
- valve stem taper
- stem/stem nut thread wear
- abnormal line voltage
- degraded stem lubrication
- degraded gearcase lubrication
- worm gear tooth wear
- restricted valve stem travel
- obstructions in valve seat area, roughness of valve guides
- abnormal differential pressure or fluid flashing
- disengagement of motor pinion gear

A description of each of these detectable abnormalities can be found in ref. 1. Two representative abnormalities are illustrated and described below.

3.2.1 Stem Packing Tightness

Figure 10 shows the change in amplitude of the worm gear tooth meshing frequency peak and the frequency shift of the motor slip peak that accompany an increase in stem packing tightness (as quantified by the torque applied to the packing gland bolts). The ordinate scale is unchanged for the three operating conditions. Recall that an increase in slip frequency corresponds to a decrease in motor shaft speed, which is to be expected with the increased stem load resulting from the more compressed packing. The increased height of the WGTM peak is indicative of the higher contact forces between the worm and the worm gear resulting from the increased valve stem load. Additional low-frequency peaks, observed at the greatest packing tightness, reflect increased running load components associated with the stem nut rotational frequency and its harmonics.

3.2.2 Worm Gear Tooth Wear

Detection of worm gear tooth wear is illustrated by the time-domain plots of Fig. 11. The uppermost plot shows a 10-s, midstroke portion of the motor current signature at the start of the test, that is, the baseline condition. The ordinate scale has been expanded and offset from zero to show clearly the cyclic variations in motor current that result from motor slip (frequency = 2.33 Hz; period = 0.429 s) and the engagement of individual teeth of the worm gear with the worm (which occurs with each revolution of the worm, i.e., each 65.16 ms for this particular motor operator). The worm gear was removed from the operator and two nonadjacent teeth were altered with a hand file; ~0.0065 in. of material was removed from one tooth and ~0.005 in. from the other, later-engaging tooth. (In each case, we attempted to remove material symmetrically from both sides of the tooth and from across the entire tooth width and to maintain tooth surface angles.)

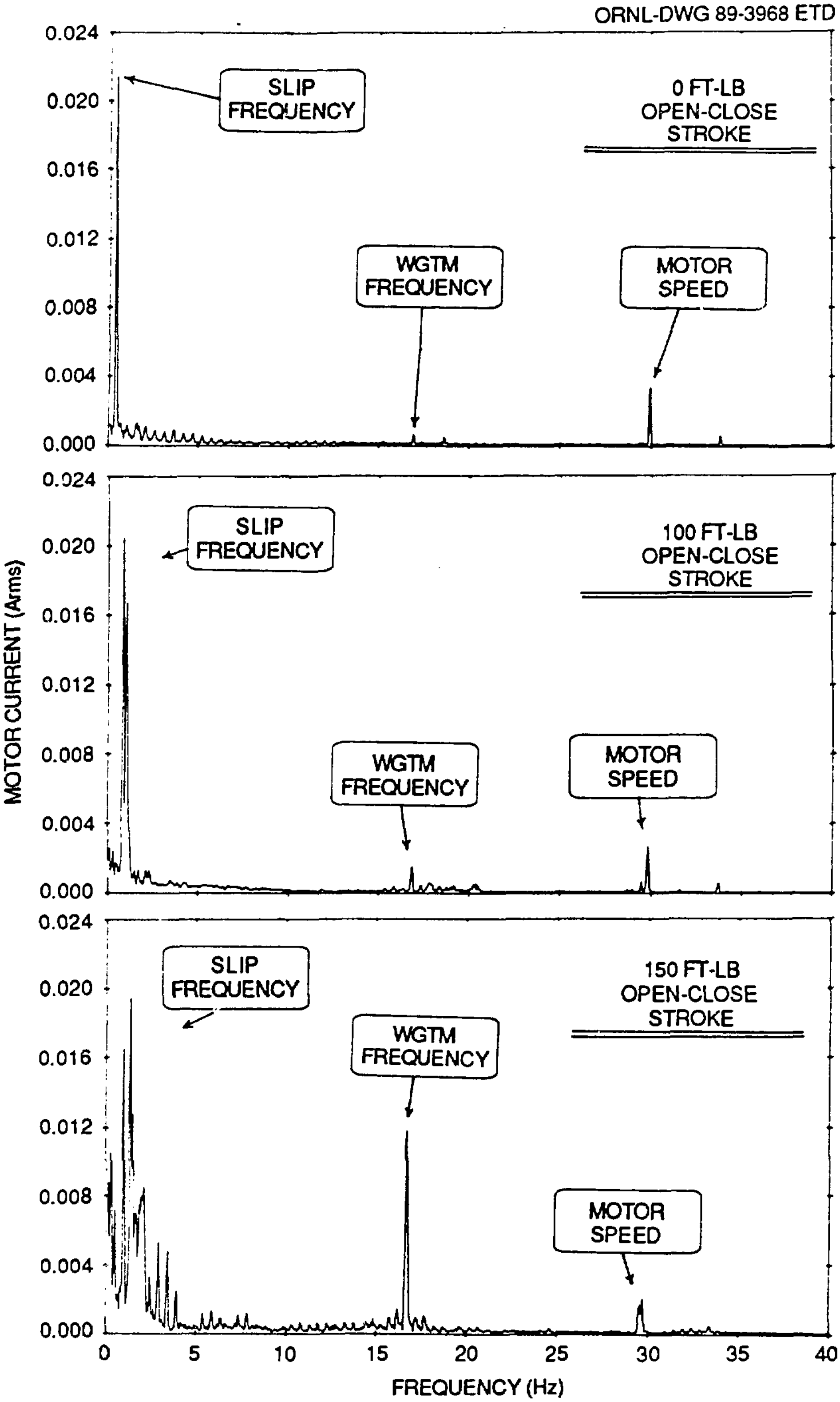

Fig. 10. Frequency-domain motor current signatures for the same MOV at three levels of packing tightness.

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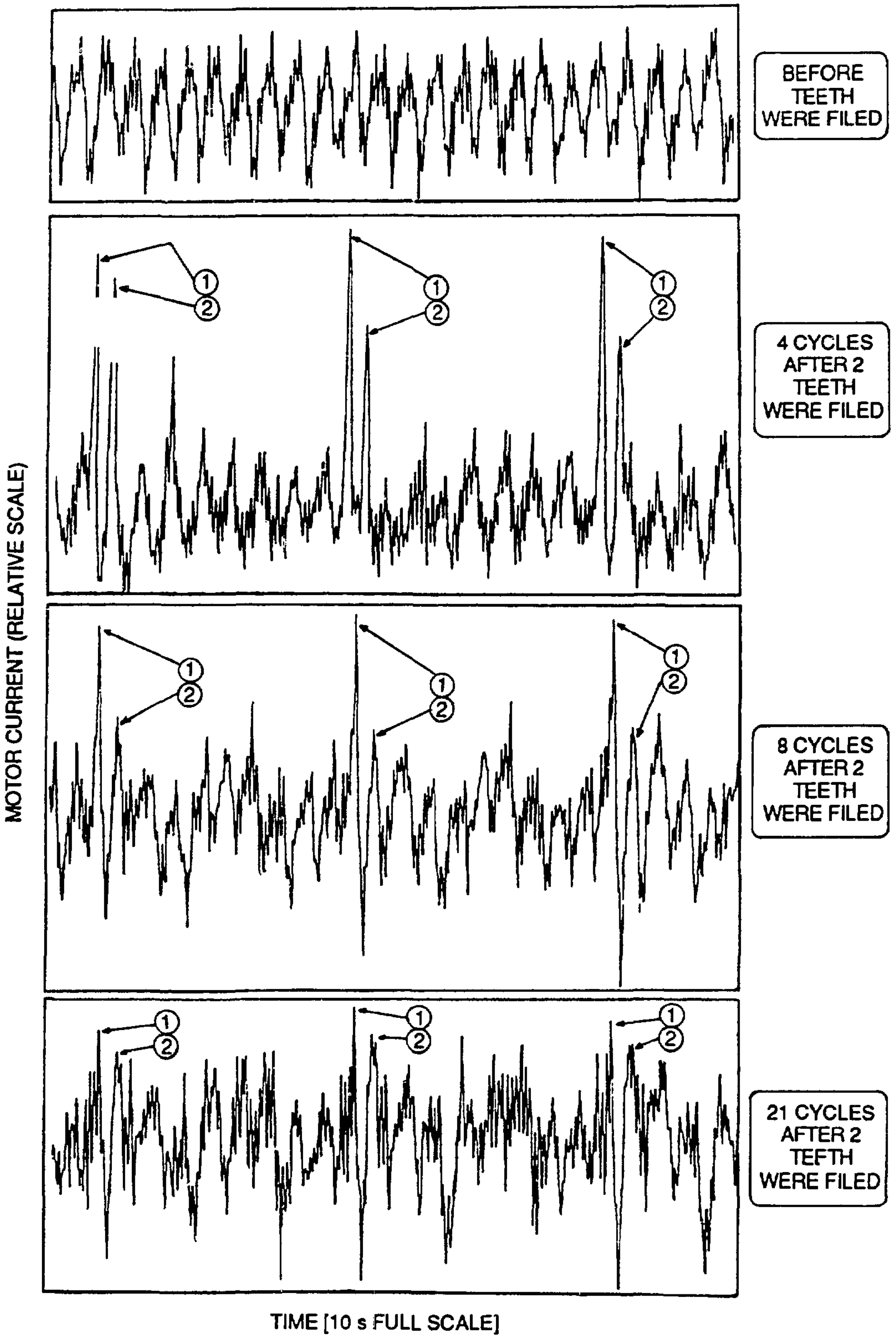

Fig. 11. Time-domain motor current signatures before and after the introduction of a worm gear defect.

After reinstallation of the defected gear the operator was actuated repeatedly, giving the results shown in the lower three traces of Fig. 11. There can be little doubt that the presence of two strong, closely separated peaks corresponds to the successive meshing of the two altered gear teeth with the worm. Note that the more heavily filed tooth gives the larger transient and that the new pair of peaks recur each 3.7 s, which is the time required for one complete revolution of the worm gear. Equally interesting, the peaks became less pronounced as the operator was stroked repeatedly, presumably the result of gradual "wearing in" of the implanted defects.

4. CONDITION INDICATION OF OTHER MECHANICAL DEVICES

While the bulk of ORNL experience with MCSA has been in connection with MOVs, motor current signatures have also been obtained from a number of other devices, namely:

- fractional-horsepower reciprocating vacuum pump
- 150-hp centrifugal water pump
- window air conditioning unit
- fractional-horsepower squirrel cage blower
- fractional-horsepower gear train

Each application was successful in the sense that highly reproducible signatures were obtained, each possessing distinctive features that could be linked without ambiguity to specific physical phenomena. However, because of programmatic considerations, no opportunity existed to study the sensitivity of the signatures to implanted or naturally occurring equipment defects as had been done for MOVs. Nonetheless, the following two examples are presented briefly to provide a somewhat enlarged perspective on additional areas in which MCSA may have application.

4.1 LABORATORY VACUUM PUMP

A motor current noise frequency spectrum for a laboratory vacuum pump is shown in Fig. 12. This signature is notable for its large number of distinct, identifiable peaks. The single-cylinder reciprocating pump tested is V-belt driven at a speed reduction of about 4.5:1, and two harmonics of the pump pulley rotation speed are visible in addition to the fundamental at 6.5 Hz. The dominance of the second harmonic (13.0 Hz) is attributable to the two direction (and load) reversals that the piston and its connecting rod undergo with each revolution of the pump shaft as a result of the crankshaft construction. The irregularity produced by the periodic passage of the joint in the V-belt is also seen to introduce strong peaks, at the second harmonic of the joint passing frequency (10 Hz) in particular. The magnitudes of the belt-generated spectral components were observed to be strongly influenced by belt tension; the data shown here were obtained with the V-belt fairly slack, which resulted in some belt "whip" during operation.

4.2 SMALL CENTRIFUGAL BLOWER

A small (1/30-hp, 3600-rpm) squirrel cage blower was tested at various load and flow conditions. Figure 13 illustrates that as the blower discharge flow area was increasingly blocked, the motor speed increased as indicated by the

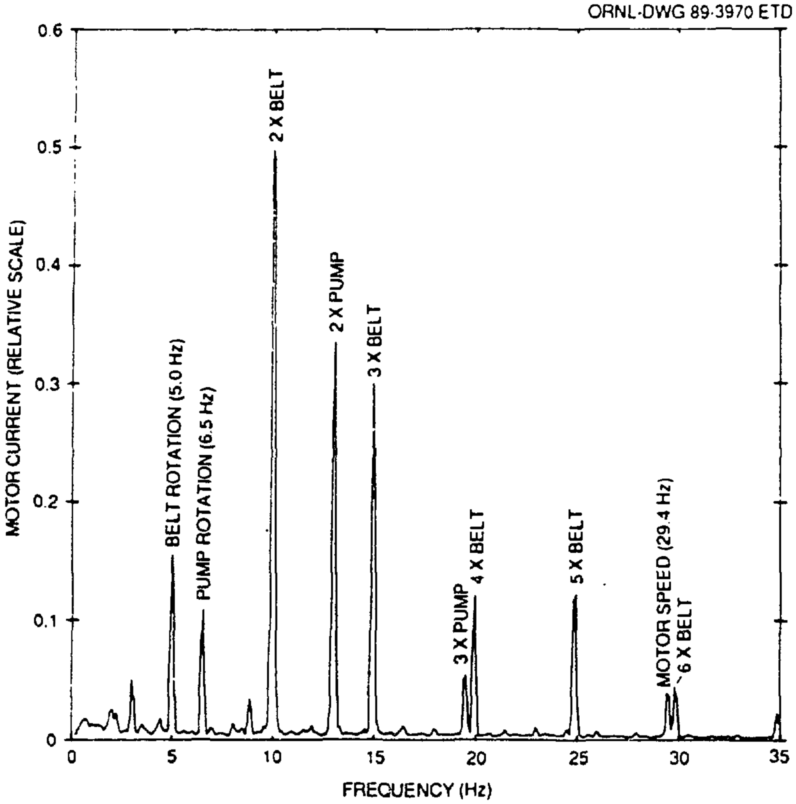

Fig. 12. Frequency-domain motor current signature for a reciprocating laboratory vacuum pump.

readily observable decreases in the motor slip frequency. These data suggest that MCSA applied to a blower of this type could provide remote indication of air flow and/or pressure drop in a piping or ductwork system without a need for conventional flow or pressure transducers or a tachometer.

5. APPLICABILITY TO OTHER MACHINERY

Although application experience is presently lacking in areas outside those already cited, it is likely that MCSA will provide a highly sensitive, selective, and cost-effective means for on-line monitoring of the condition of a wide variety of heavy industrial machinery. For example:

- motor-driven compressors and pumps
- rolling mill stands
- mixers and crushers
- fans and blowers
- material conveyors

Likewise, it appears that MCSA may prove useful in production line preshipment testing of some motor-driven consumer appliances and lighter industrial equipment, namely:

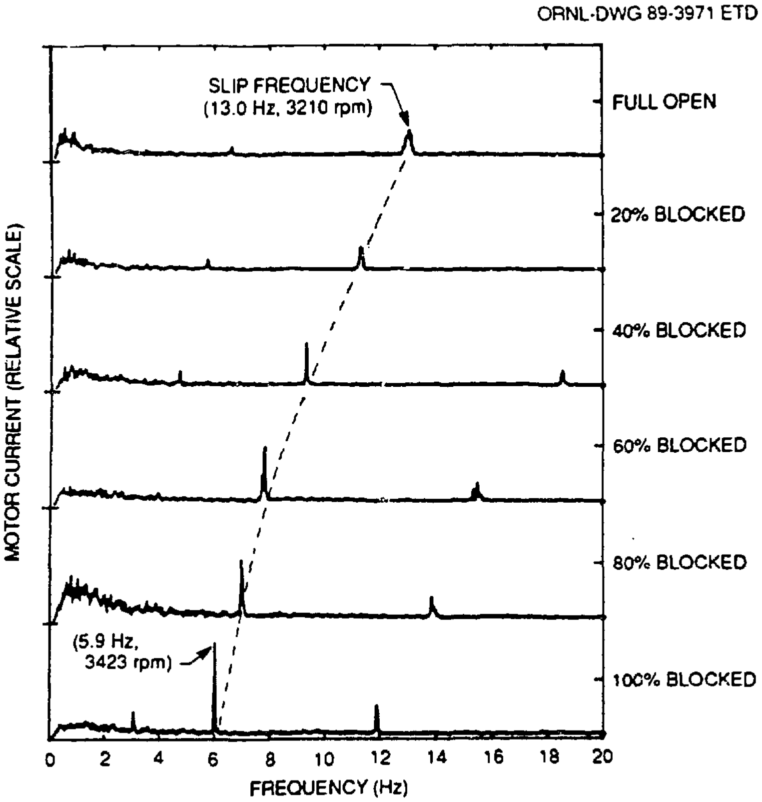

Fig. 13. Frequency-domain motor current signature for a small blower with various degrees of flow blockage.

- refrigerating equipment and heat pumps
- washing machines and dishwashers
- audio/video recording/reproduction equipment
- computer disk drives

Neither the authors nor their employer currently has plans to explore the above application possibilities, but mechanisms for transferring the MCSA technology to prospective users are available, through, for example, nonexclusive licensing agreements tailored to the licensee's needs. One such license has already been issued, and several other private enterprises have expressed an interest in or are presently negotiating licensing arrangements.

6. CONCLUSIONS

Extensive test data support the conclusion that MCSA is a useful tool for monitoring the mechanical and electrical condition of MOVs, particularly in relation to their operational readiness. Experience with motor-driven machinery other than MOVs, though limited, strongly suggests that MCSA is equally applicable to monitoring present condition and to diagnosing impending trouble in a wide variety of consumer and industrial equipment. MCSA has a number of inherent strengths, the most notable being that it

- provides nonintrusive monitoring capability at a location remote from the equipment;

- provides degradation and diagnostic information comparable to conventional instrumentation (e.g., accelerometers) but without the attendant disadvantages of added sensors and signal cables;

- offers high sensitivity to a variety of mechanical disorders affecting operational readiness;

- offers means for separating one form of disorder from another (selectivity);

- can be performed rapidly and as frequently as desired by relatively unskilled personnel using portable, inexpensive equipment;

- is equally applicable to high-powered and fractional-horsepower machines, ac and dc motors.

It is the authors' hope that MCSA will receive consideration and additional scrutiny in the future by engineers from diverse industries and equipment manufacturers.

7. REFERENCE

1. H. D. Haynes, *Aging and Service Wear of Electric Motor-Operated Valves Used in Engineered Safety-Feature Systems of Nuclear Power Plants, Vol. II: Aging Assessments and Monitoring Method Evaluations*, NUREG/CR-4234, V.2, Oak Ridge National Laboratory (in press).