Consolidated Fuel Reprocessing Program

DYNAMIC CONSIDERATIONS IN THE DEVELOPMENT OF CENTRIFUGAL SEPARATORS USED FOR REPROCESSING NUCLEAR FUEL*

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Dynamic Considerations in the Development of Centrifugal Separators Used for Reprocessing Nuclear Fuel

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ABSTRACT

The development of centrifugal separators has been a key ingredient in improving the process used for reprocessing of spent nuclear fuel. The separators are used to segregate uranium and plutonium from the fission products produced by a controlled nuclear reaction.

The separators are small variable speed centrifuges, designed to operate in a harsh environment. Dynamic problems were detected by vibration analysis and resolved using modal analysis and trending. Problems with critical speeds, resonances in the base, balancing, weak components, precision manufacturing, and short life have been solved.

INTRODUCTION

The fuel cycle for commercial nuclear power reactors involves the processing of uranium and plutonium in many forms. For uranium, the naturally occuring oxide is mined and milled, converted to uranium hexafluoride, enriched to increase the concentration of the fissionable U-235 isotope, fabricated into oxide fuel pellets, loaded into reactor fuel rods, used as fuel in the reactor, then unloaded and reprocessed. Reprocessing the spent fuel, which is irradiated material, poses several technical challenges which are being addressed by the Fuel Recycle Division (FRD) of the Oak Ridge National Laboratory (ORNL).

Uranium and plutonium can be recovered from irradiated nuclear fuel using a liquid-liquid extraction process. This process involves preferential transfer of uranium and plutonium between an organic solvent and an aqueous phase to remove the fission products. The Purex process uses tributyl phosphate (TBP) in normal paraffin hydrocarbon as the organic solvent and a nitric acid solution as the aqueous phase. Nitric acid and radiation from the fission products break down the TBP into compounds which adversely affect the removal of fission products from the uranium and plutonium, so contact time between the organic and aqueous stream must be minimized to reduce the degradation of TBP.

Gravity settlers have been previously used to separate the two process fluids, but these settlers required a relatively long residence time to separate the two streams, exposing the TBP to a considerable amount of radiation. Centrifuge separators, known as contactors, which separate the streams using centrifugal force were developed to decrease radiation damage to the solvent.

The Integrated Equipment Test (IET) facility in the Consolidated Fuel Reprocessing Program (CFRP) at ORNL was designed to test prototypic equipment for nuclear fuel reprocessing plants. The facility is equipped with solvent extraction contactors to simulate the co-decontamination stage of the Purex process. Several banks of advanced design centrifugal contactors are used in the solvent extraction system. A schematic of the advanced centrifugal contactor is shown in Figure 1.

In the advanced centrifugal contactor, the aqueous and organic solutions enter the contactor from opposite sides into the annular gap between the stationary housing and the rotor. The two solutions are intimately mixed in the annular gap by couette mixing to promote mass transfer. The mixture flows from the annular gap into the rotor through an opening at the bottom and is accelerated to provide quick separation of the two phases. The separated phases flow over weirs at the top of the rotor to collector rings on the housing, passing on to subsequent stages.

The contactors must be maintained by a remote manipulator device due to the high radiation field in the process cell. Some of the contactors installed in the IET facility were designed to permit fast change out of the motor-rotor assembly. The rotor is connected to and suspended from the drive motor by a rigid connector. The entire assembly can be removed from the contactor housing by disconnecting the motor mounting bolts shown in Figure 1. This arrangement requires a well balanced rotor and a precision drive motor to minimize dynamic problems and maximize machine life in this harsh environment. The critical nature and use of the equipment, as well as the characteristic dynamic sensitivity of overhung rotor machines, requires machinery monitoring to determine the relative health of the drive motor. Vibration analysis has been, and continues to be, used to monitor the drive system and to improve rotor design.

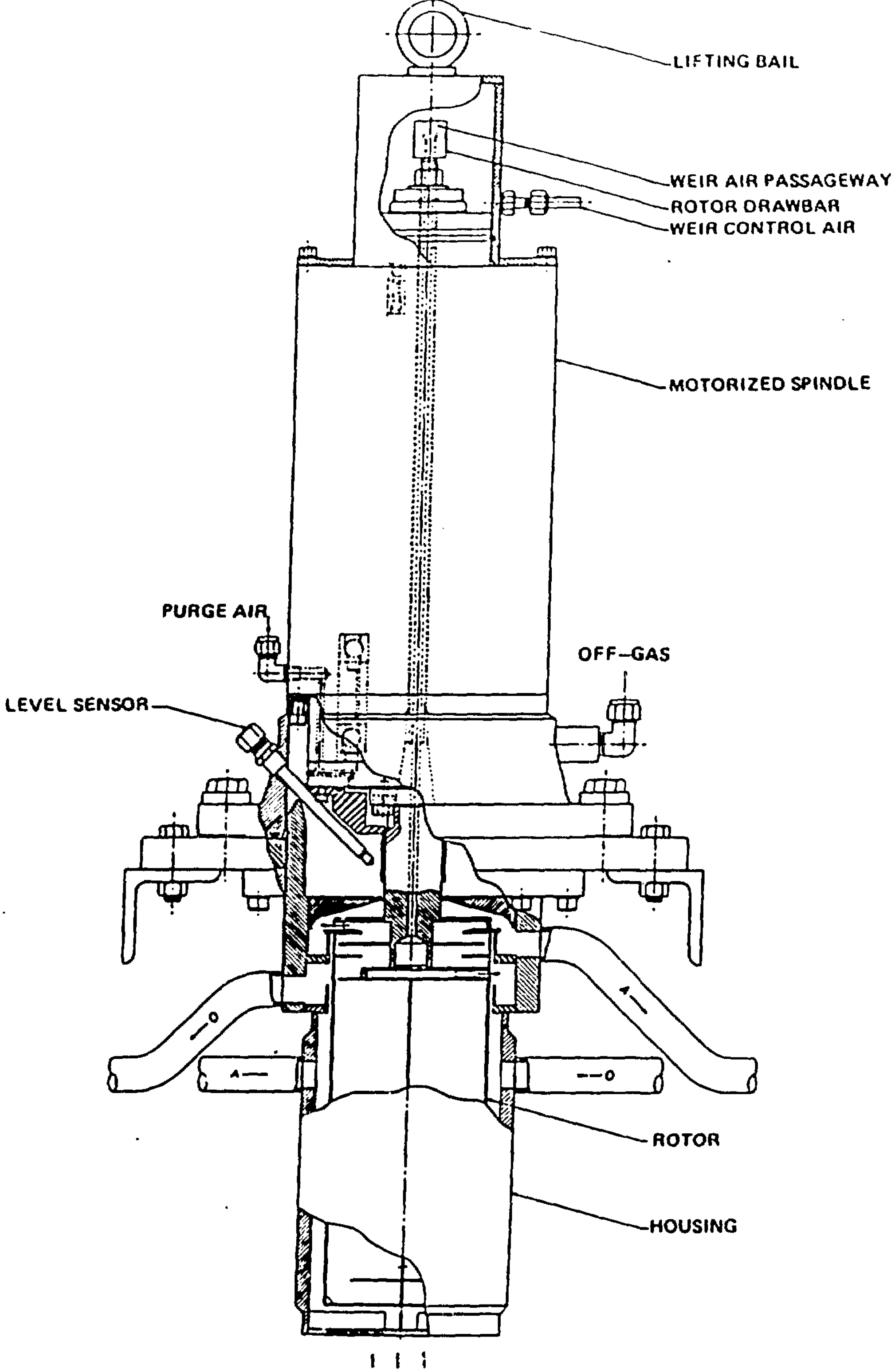

Figure 1. Contactor Schematic Diagram

THE DEVELOPMENT CYCLE

The development of these small, moderate to high speed centrifuges took place in stages:

1. production of a general specification for outside designs and procurement.
2. production of in-house design
3. fabrication of modified in-house design
4. testing of commercially available drive systems
5. iterative testing and redesign of in-house model
6. completed design, specification, and manufacture of final model

Experimental dynamic testing and analysis techniques have been shown to be powerful tools for the solution of dynamic design and operation problems. The original contactor design and specification did not include an evaluation of contactor dynamic concepts. It has been found in Oak Ridge that most dynamic concerns can be addressed in a cost effective manner in the design stages, even if only to indicate a need for testing after fabrication. Much time could also have been saved since this development effort took over 14 months to accomplish all the testing and redesign work.

The dynamic analysis techniques used for contactor testing were a thorough combination of commonly known and well understood methods: modal analysis, balancing, trending of single plane spectral data and broad-band velocity measures, waterfall analysis, and structural modifications. Each of these techniques were needed to resolve some concern during a phase of the tests and redesigns.

TESTING

Two sizes of contactor rotors have been tested: a large contactor, 12 cm rotor diameter, and a smaller, 5.5 cm rotor diameter. The same basic rotor design was used for both sizes of contactors. Variations in size and design were made for specific speed and flow rate needs. The contactors are made of 304L stainless steel. The small contactors are driven by a permanent magnet DC motors. The large contactors are driven by high precision AC motorized spindles that are generally used in machine tools. Steady state testing was done at moderate rotating speeds, usually 4,000 RPM (66.7 Hz).

All designs were tested using accelerometers mounted on the free end of the motor. With the contactors directly mounted to the motors, the only load bearings are those in the motor. With the motor mounts close to the lower bearing, the prevalent motions and descriptive frequencies are most easily detected on the free end.

Test equipment included accelerometer signal conditioners, a single-channel FFT analyzer (with signal integration and waterfall capabilities), a broad band velocity meter, a balance analyzer, and a modal analyzer.

SMALL CONTACTOR TESTING

The first small units were designed and fabricated with little initial concern for dynamic performance. These units experienced high vibration and noise levels, as well as rubbing, from the beginning of operations. Motors and rotors were dynamically tested to determine the cause of the vibration, rubbing, and noise. This testing was done with a motor and rotor connected, and placed on a thick foam rubber pad (instead of mounted in a test fixture) to simulate a "free-free" constrained state which often allows vibration problems to be detected more readily.

Vibration measurements were made using a balancing analyzer with acceleration or velocity amplitude and phase measurements, and a single channel FFT analyzer. Proximity probes were used to measure low speed run-out (eccentricity) of the rotor barrel. Imbalance and eccentricity were readily apparent from the spectra generated. The high amplitudes and little significant harmonic content shown in Figure 2 were typical of the measurements made. Broad band levels of up to 1.1 ips and 1.2 g were measured on these units. The descriptive bearing frequencies were in the noise floor of the wide spectral measurements, but could be detected by selective filtering of the accelerometer signal.

Resonant frequencies and critical speeds were found to be above the operating range, and therefore not a major concern, by using impact modal tests with a two-channel modal analyzer and run-up tests on a single channel FFT analyzer. Run-up testing involved gradually increasing or decreasing the running speed while continuously acquiring and storing spectral data in an analyzer. Peak averaging (Figure 3), in which the highest level is stored for any frequency component of the spectrum, demonstrates the frequencies of the lesser damped critical speeds. Waterfalls, or spectral map capability, also can be used to sequentially plot spectra obtained during a run-up test, as seen in Figure 4. Vibration amplitude increases at a critical speed, and although there are often several critical speeds and resonances identifiable in a wide band spectrum, the run-up tests and modal analysis showed only one significant critical speed. The transfer function from a static modal analysis is shown in Figure 5.

For the small contactors operating steady state, typical broadband levels of 0.6g and 0.5 ips were seen. Enhanced balance requirements and a stiffer connector were recommended for the next design/fabrication cycle. The motors were found to exhibit behavior typical of small DC motors with ABEC Grade 3 or less bearings.

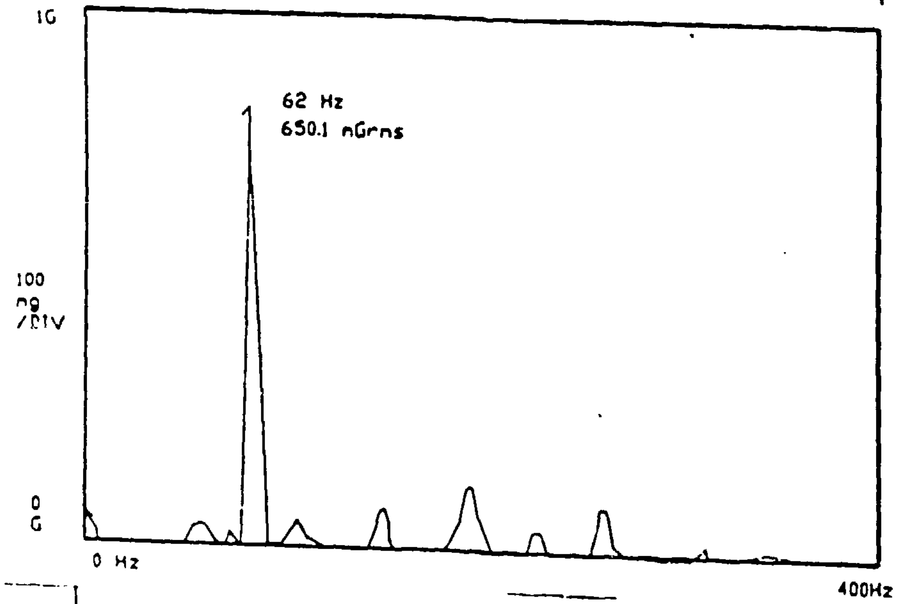

Figure 2. Early Contactor Vibration Spectrum

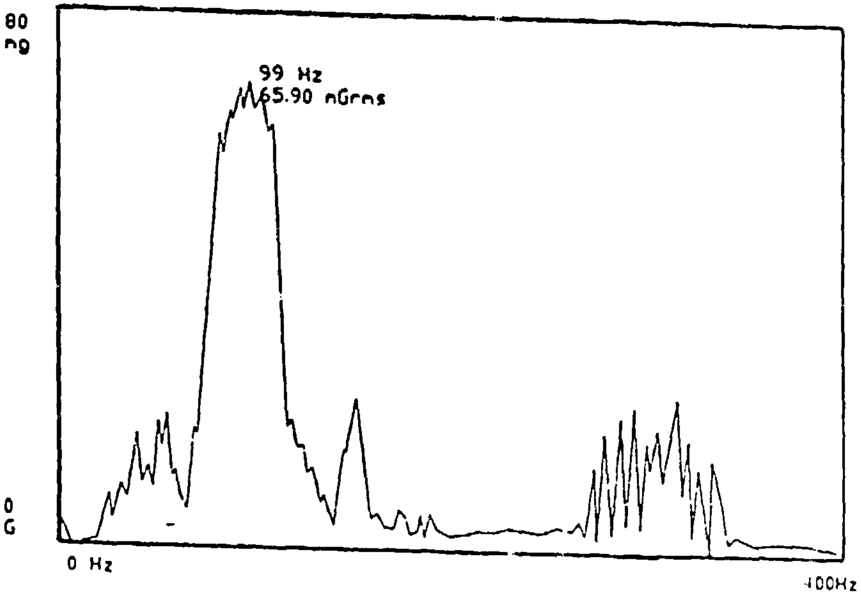

Figure 3. Peak Averaging Impact Test Spectrum

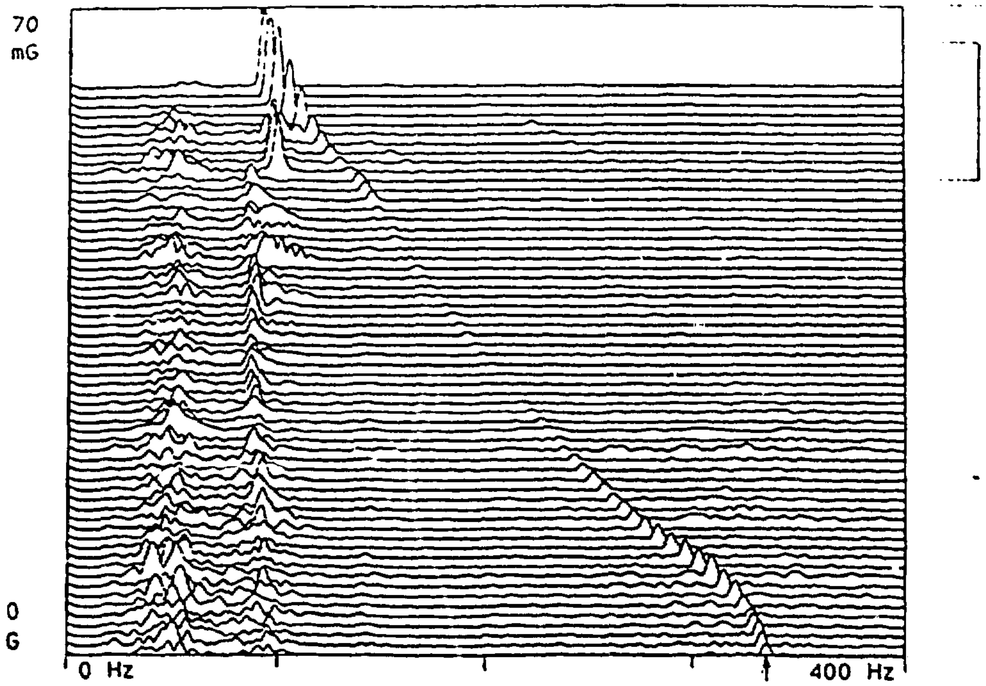

Figure 4. Run-Up Waterfall Spectra

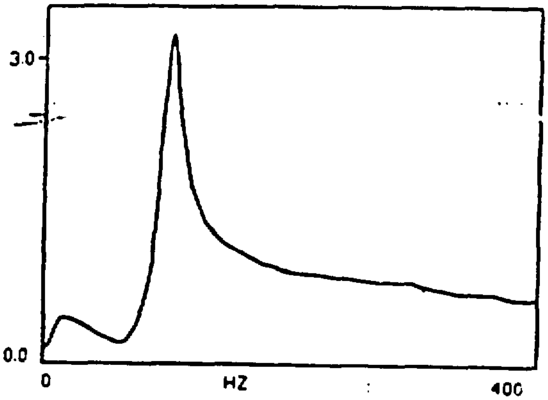

Figure 5. Modal Transfer Function - Magnitude

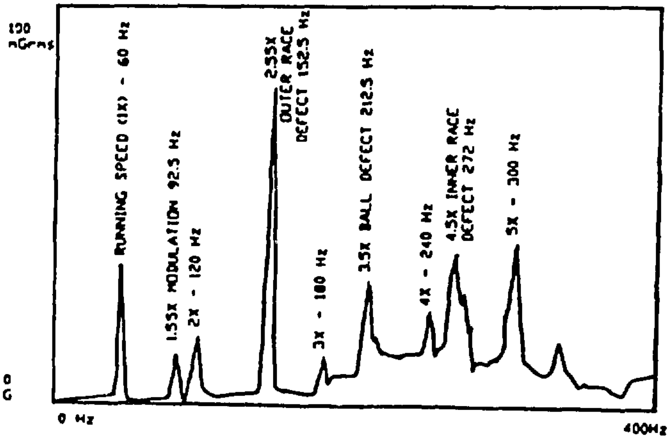

Figure 6. Bearing Frequencies

Next, several contactor rotors were redesigned and/or reworked to provide a balancing capability (balance rings), and precision machined to eliminate eccentricities. Two balance ring designs were tested. The "high mass" design (a large mass balance ring next to the connector) was found to be superior in dynamic performance. Typical vibration levels in the simulated free-free state, for pre-balanced rotors, were 0.3 ips and 0.35 g. Very narrow band analysis to observe detailed power levels at various frequency bands did not provide any better analysis of the bearings or critical speed than the wider band data shown in the figures. ABEC Grade 7 bearings were specified for the next motor redesign.

During the next four months, the small contactors underwent another redesign and fabrication iteration. Vibration testing was completed on 12 of the new units located in a small lab on impermanent, loose mountings. Vibration levels were considerably smoother, 0.1 g or 0.15 ips, but some moderate imbalance and looseness was seen (Figure 7).

Fourteen small contactors and motors of the newest design were then installed in a production test stand for in-place and on-line testing for flow optimization studies. Baseline vibration data was taken for long term trending studies. A hard-wired vibration monitoring system, using accelerometers, was installed and calibrated. Initial vibration levels were reasonable, but moderately high as seen in Figure 8.

The final stages of the development process took place over the next three months. New AC motors with ABEC Grade 7 bearings were tested and found to be dynamically superior to the DC motors. The stiffness of the AC motors was greater and the vibration levels were less than the DC motors. A radical, simpler redesign of the rotor was made which allowed easier fabrication and eliminated the balance ring. This new rotor design was tested and found to have superior dynamic properties (higher critical speeds and resonance frequencies and less balancing required).

Some commercially available and foreign designed small contactors were also tested. Critical speed evaluations were done using run-up tests and waterfall plots to determine the maximum safe operating speed. The waterfall tests were found to be quite helpful when the calculated critical speeds and the static modal analysis of the contactor structure were in disagreement. The critical speeds corresponded closely to the lower order bending modes, as is often the case.

The final design of the small contactors uses an intrinsically balanced rotor. Dynamic testing proved this design to have the lowest vibration levels, highest stiffness, highest frequency bending modes, and highest critical speeds of any previous design. A number of identical rotor parts can be manufactured and assembled using modern fabrication methods such as electron discharge machining to reduce the time and cost of manufacture.

LARGE CONTACTOR TESTING

Larger contactors built for an in-place operational test under actual flow conditions were operated for two months to obtain actual flow data. Vibration data trending of the 16 contactors was initiated after one motor failed due to corroded bearings. Bearing frequencies were calculated and confirmed by the measurements, as shown in the spectrum in Figure 6. Vibration levels of 0.08 ips and 40 mg were typical. The trending was done to estimate the remaining life of the units (ie. the bearings). Trending was accomplished by recording the amplitudes at the running speed, descriptive bearing frequencies, pass frequencies, and structural resonances. Twelve measurements were taken on each machine over a two month period, and it was estimated (at a 50 percent confidence level) that the remaining life of the worst unit was greater than the 1,000 hrs required to complete testing. The motors were designed for a 30,000 hr life.

An additional test run of the larger contactors was accomplished three months later. It was significant to note that, even in the presence of corrosive fluids, no significant changes were detected on any of the 16 units.

The large contactor with the highest vibration levels experienced during the in-place trending test was placed in a specially designed test stand for long term operation to understand the long term dynamic characteristics of the large contactors. This was a "run-to-failure" test on the contactor/motor assembly. The bearings on this unit had been flooded by the corrosive fluids in the system, but the vibration levels remained relatively constant. The bearings have shown little wear, as proved by the bearing frequency and high frequency analysis. A multiple spectral plot of this contactor is shown in Figure 9.

CONCLUSIONS

The identification and resolution of the dynamic problems of the contactor rotors was a relatively easy task for a well equipped analyst. Many of these dynamic problems were discovered and resolved effectively in the early testing phases, but all problems were ultimately identified and resolved. The use of the entire field dynamic testing capabilities of the vibration analyst quickly led to an increased understanding of the contactor behavior and design improvements. It is interesting to note that most of the analyses were made possible by a single channel FFT analyzer, probably one of the simplest tools in the Oak Ridge vibration laboratory.

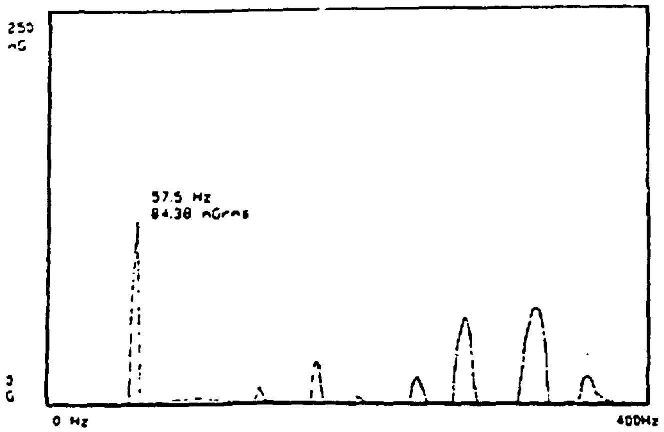

Figure 7. Redesigned Contactor Vibration Spectrum

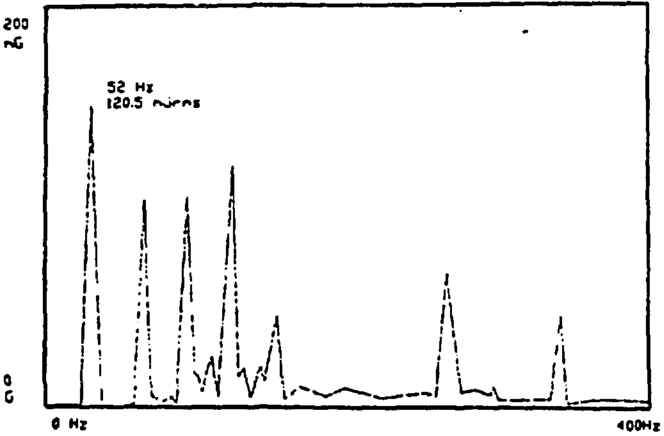

Figure 8. Test Stand Vibration Spectrum

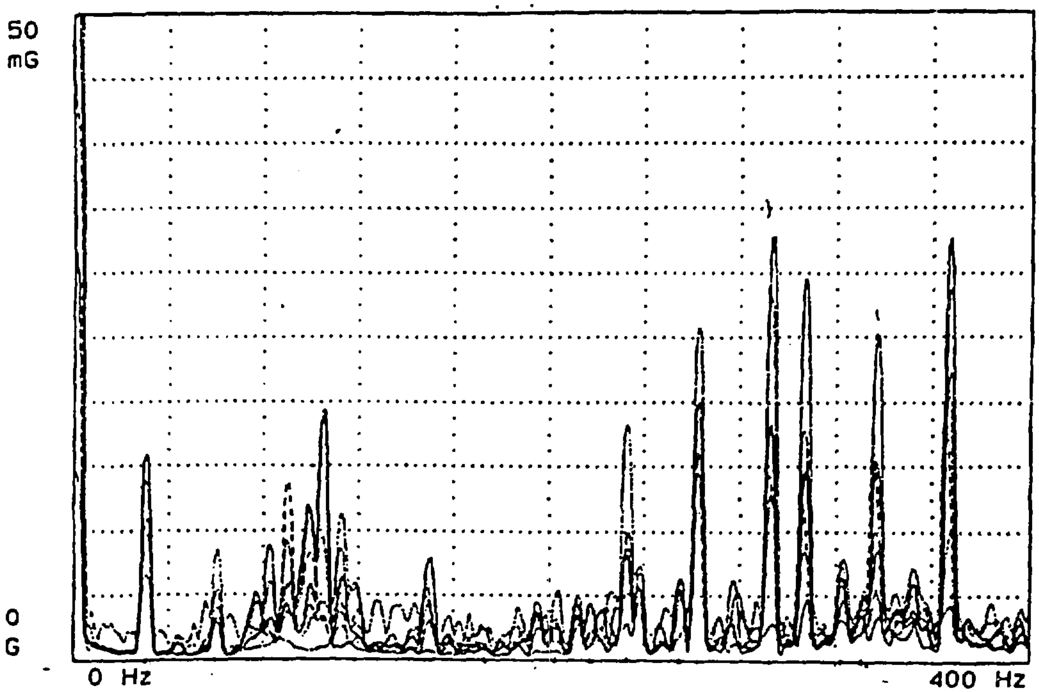

Figure 9. Multiple Spectra of Same Contactor