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DEVELOPMENT OF DIESEL ENGINE DIAGNOSTICS FOR U.S. COAST GUARD CUTTERS

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16. Abstract

This program involved an investigation of techniques to perform engine fault diagnosis on the large medium-speed diesel engines used as main propulsion power plants in medium- and high-endurance Coast Guard cutters. Two engine diagnostic parameters were defined and selected as the parameters of interest. They were (1) Instantaneous Crankshaft Angular Velocity (ICAV), which directly relates to the developed power contribution for each cylinder, (2) Dynamic Crankcase Pressure (PKD), which relates to the amount of gas leakage past the piston rings and into the crankcase. Prototype instrumentation was designed and developed to measure relative values of these parameters, and tests were conducted with several operating engines, some of them in Coast Guard cutters. Results of the development and test work were generally encouraging, but not definitive. This effort is therefore viewed as a step toward achieving the program goals. The report contains recommendations for further work.

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PREFACE

The Southwest Research Institute, under contract to the U.S. Department of Transportation, Transportation Systems Center (TSC), has developed a method for testing equipment for fault diagnosis of large marine diesel engines. Diagnostic techniques considered for prototype modification have been limited to those that can be applied without mechanical modification to in-service Coast Guard engines. These techniques will yield the widest range of useful diagnostic information for the least expenditure of time and money. The project monitor for TSC is R. Walter. F. Weidner is the project officer for the U.S. Coast Guard.

We wish to acknowledge the cooperation and assistance of personnel from the following ships and organizations in the pursuit of the objectives of this project:

U.S. Coast Guard Cutter COURAGEOUS (WMEC 622)

U.S. Coast Guard Cutter DURABLE (WMEC 628)

U.S. Naval Training Center, Great Lakes IL

ALCO Power Inc., G.E.C. Diesels, Ltd., Auburn NY

Fairbanks Morse Engine Division, Colt Industries, Inc., Beloit WI.

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1. SUMMARY AND CONCLUSIONS

This report describes the work accomplished in Task 4, "Engine Diagnostics," of Contract DOT-TSC-920, Phase II. The primary objectives of this task were to examine candidate methods [1] of diesel engine fault location and diagnosis, to select promising methods for development, and to implement them in a cost-effective manner. To this end, two diagnostic parameters were chosen and techniques developed for their measurement. The first is Instantaneous Crankshaft Angular Velocity (ICAV) and the second is Dynamic Crankcase Pressure (PKD). In order to identify the position of a particular cylinder in the data readout record, an electrical signal was generated by a sensor attached to the desired cylinder's fuel injection line (generally No. 1 in the firing order). This data synchronization (SYNCH) signal gives an approximate indication of piston top dead center (TDC) since it coincides with injection for the target cylinder.

The introductory section of this report provides an overview of project objectives and a resume of germane background information. The selected diagnostic parameters and their measurement techniques are described next, followed by a description of laboratory prototype equipment development required to make the measurements. Test procedures, results, and conclusions from each of a series of tests on eight large diesel engines (including some in actual shipboard installations) are reported along with results from two smaller diesel engines at the Southwest Research Institute (SwRI). Finally, specific recommendations are made regarding future work with these fault diagnosis methods.

Conclusions to be drawn from the program are as follows:

> The ICAV waveforms of the various large diesel test engines responded in an often very subtle (and usually very complex) manner to induced power imbalance conditions in a single cylinder; however, inspection of the data demonstrates that ICAV changes from baseline <u>were evident</u> with induced power imbalance and for this reason the technique shows promise as a means of diagnosing and locating power imbalances caused by malfunctions in large diesel engines. The ICAV waveform changes for large engines are not so easily correlated with defects as they are for smaller engines; therefore, ICAV needs considerable equipment development and baseline engine data refinement to adequately define the design parameters of a practical diagnostic system. More particularly, ICAV test work during this project demonstrated that large diesel engines, because of their long crankshafts, operate (even at idle speeds) fairly near the first major crankshaft torsional resonance. This torsional resonance tends to obscure the crankshaft rotational contribution of

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[1] Hambright, R.N., J.O. Storment, and C.D. Wood, <u>Selection of a Prototype Engine Monitor for Coast Guard Main Diesel Propulsion Engines</u>, Report No. DOT-TSC-USCG-79-3, Department of Transportation-U.S. Coast Guard, April 1979 (CG-D-131-76, NTIS AD A071712).

2. BACKGROUND AND INTRODUCTION

Southwest Research Institute (SwRI) began work in November 1974 on Contract DOT-TSC-920 for the Transportation Systems Center of the U.S. Department of Transportation and the U.S. Coast Guard Office of Research and Development. The initial part (Phase I) of this program involved an investigation of methods to reduce fuel consumption and exhaust emissions of large in-service diesel engines used in both locomotives and several classes of Coast Guard cutters. Phase I was completed in September 1975, with the publication of a report[2] that summarized the findings and conclusions and presented a list of recommendations as to the course that future (Phase II) efforts should take.

Part of the Phase I effort was to investigate and evaluate maintenance practices actually used with these large diesel engines. It subsequently developed that available information was not adequate to reach the goal of accurately determining the quantitative relationship between user maintenance practices and resultant effects on engine performance and emissions. As a positive result, however, this effort did produce valuable insight regarding the types of maintenance programs applied to these engines.

Specifically, the Coast Guard at that time employed an "as-required" maintenance program for the engine center section, which includes pistons, piston rings, cylinder liners, main and connecting rod bearings, and the crankshaft. Under this program standard instrumentation methods are used to determine the condition and performance of center section components. These methods include periodic analysis of the spectrochemical and physical properties of the lubricating oil and monitoring of operating parameters such as crankcase pressure, exhaust manifold pressure, intake manifold or air box pressure, and exhaust gas temperatures for individual cylinders. Values of these parameters, plus wear metal concentrations from lube oil analysis, are plotted as functions of engine operating time to obtain a time-based trend analysis of engine condition. Additionally, a final indicator of overall engine condition is provided by periodic full-power trials wherein the ability of the ship to meet certain performance criteria is determined. Individual cylinder values of exhaust temperature, firing pressure, and fuel pump rack setting are recorded during full-power operation and later analyzed to determine if the values are within the engine manufacturer's specified limits.

The "as-required" maintenance program, which is entirely conventional in nature, was in general found to be working well. There were, however, a

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[2]Storment, J. O., C. D. Wood, and R. J. Mathis, A Study of Fuel Economy and Emission Reduction Methods for Marine and Locomotive Diesel Engines, Report No. DOT-TSC-OST-75-41, Department of Transportation-U.S. Coast Guard, September 1975 (CG-D-124-75, NTIS AD A009214).

3. DIAGNOSTIC PARAMETERS

3.1 Candidate Parameters and Selection Methods

The following compilation of engine operating parameters lists those things which may be measured to gauge the condition of a large diesel engine short of tearing it down. Some are commonly used, others are more exotic; but in any case, this list embraces all the candidate diagnostic parameters which were evaluated before selection of those that would be implemented during the course of project experimental work.

- engine speed
- engine output (shaft) torque
- horsepower
- main bearing temperature and oil pressure
- coolant into engine--temperature, pressure, and flow rate
- coolant out of engine--temperature, pressure, and flow rate
- oil sump temperature
- common (average) exhaust duct temperature and pressure
- common exhaust duct instantaneous temperature and pressure
- individual exhaust port average temperature and pressure
- individual exhaust port instantaneous temperature and pressure
- fuel inlet temperature, pressure, and flow rate
- return fuel temperature, pressure, and flow rate
- intake manifold or air box temperature and pressure
- air intercooler temperature and pressure
- turbocharger air temperature and pressure
- oil cooler inlet temperature and pressure
- turbocharger oil return temperature and pressure
- sea water injection temperature and pressure
- instantaneous crankshaft angular velocity (ICAV)
- cylinder pressure vs. time relationship (P-T)

cycle engine), it can be seen that torque variation is reduced as we decrease angular spacing (i.e., increase frequency) of cylinder firings. However, even with firing impulses spaced 90° apart, as shown here, there is still a significant peak torque impulse delivered to the rotating mass by each firing event. Each impulse results in a momentary increase in angular velocity of the crankshaft.

The ICAV instrumentation described in this report is a practical means of measuring this departure from the average crankshaft rotational value. The magnitude of ICAV change is affected by cylinder firing pressure, engine load, the total inertial mass which the engine is rotating (flywheel, gearbox, etc.), friction of the rotating components, and anything else that either adds power to or removes power from the crankshaft. So long as each firing event's positive torque contribution is uniform, negative torque or load remains constant, and if there are no other inputs to the crankshaft, then the accelerations and decelerations of the rotating mass will be of uniform magnitude. At this point we must stress that torsional resonances, which both remove and then return power (minus losses) to the crankshaft, are not yet being considered. (An analogy may be helpful here: in electrical terms, the engine load is purely resistive, with no reactive component.) If we measure and accurately record the instantaneous crankshaft angular velocity (ICAV), we can directly observe and compare each cylinder's power contribution, and it should then be possible in practice to detect and localize a defect which causes power imbalance among the individual cylinders. This has indeed been found to be the case in previous diagnostic work on small diesel engines at SwRI.

As noted earlier, if the firing events move closer together in angular displacement, as when an engine has more cylinders or is of two-stroke cycle design, the ICAV variation becomes less pronounced because the positive torque inputs begin to overlap more, and the average torque and peak torque approach the same value. In addition, the inertia of an engine's rotating mass is specifically sized during design to reduce changes in ICAV to some desired (low) value of a particular constant, K, depending on the engine's intended type of service[4]. It is thus advantageous to load an engine undergoing diagnosis by ICAV to a mild "lugging" condition in order to reduce the inertial or flywheel effect. This simplifies diagnosis since the influence of each firing event becomes more pronounced in the ICAV record.

Precise measurement of torsional vibration magnitude, which when excessive can cause rough engine operation with unacceptable vibration and possible damage at certain engine speeds, has been the primary objective of instrument designers working with rapid cyclic variations in crankshaft angular velocity. It has only been in the last few years, with the advent of economical and powerful solid-state electronic circuitry, that it has become practical to consider using these rotational velocity excursions as

[4] Standard Handbook for Mechanical Engineers, pp. 8-100.

a means to diagnose engine faults. The torsiograph[5] and its many related instruments are satisfactory for measuring the amplitude and frequency of torsional vibrations; but they are not suitable for individual cylinder diagnostic purposes since they cannot provide real-time phase angle information which serves to identify individual cylinders. These units simply allow the engine designer to determine with reasonable accuracy that the crankshaft is not being subjected to forces likely to cause failure.

When using ICAV for diagnostic purposes, the signals resulting from torsional vibrations due to the spring mass constants of the crankshaft system can generally be greatly reduced in magnitude by electrical filtering without reducing the ICAV signal components due to individual cylinder firing events. Power imbalances due to abnormal combustion and certain other engine defects can now be observed as greater or lesser crankshaft accelerations during the portion of rotation which is related to the power stroke of the particular cylinder in question. The highest engine speed that can be satisfactorily accommodated for ICAV diagnosis is dependent upon the spring mass characteristics of the crankshaft assembly in the engine under test since this establishes the lowest torsional resonance frequency of the rotating assembly. This resonance frequency must be appreciably higher than the cylinder firing rate being used for diagnosis. By suitably identifying a cylinder (usually No. 1) in the firing order, it is possible to examine the instantaneous torque contribution and the angular momentum change resulting from the firing of a given cylinder. Because of overlapping torques, engines with many cylinders are more difficult to diagnose by these means since the power impulses are much closer together and there is less tendency for the flywheel to speed up and slow down appreciably in the course of rotation. Bear in mind, however, that engines of <u>many cylinders</u> are precisely the ones in which diagnosis is extremely difficult by <u>any</u> means. It is quite common for a 16- or 20-cylinder engine to suffer a substantial defect in one cylinder and yet display such a small amount of overall power loss that, barring catastrophic failure, the problem goes completely unnoticed in normal day-to-day usage. Instantaneous crankshaft angular velocity presents a means whereby these defects can not only be found, but also attributed to specific cylinders. No alternate, easily implemented means for making this determination has been identified.

3.3 <u>Dynamic Crankcase Pressure (PKD)</u>

Virtually all large engines have some means of measuring the static or average crankcase pressure, which may be either positive or negative depending upon whether an active crankcase scavenging system is used. While this average pressure remains constant, the combustion gas leakage from individual cylinders produces small but definite rapid variations about this average crankcase pressure value. This variation is termed Dynamic Crankcase Pressure, or PKD for short. Engine defects which manifest themselves when

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[5] Bradbury, C. H., <u>Stationary Compression Ignition Engines,</u> E. & F. Spon, Ltd., 1950.

4. EQUIPMENT DEVELOPMENT

4.1 Instantaneous Crankshaft Angular Velocity (ICAV)

Early in the ICAV test work it became apparent that a bench test rig would be particularly useful in quantifying and verifying the performance of various ICAV detection methods. Figure 4.1 shows several photographs of this test set-up, which indeed proved to be quite useful. The test rig permits known variations in ICAV to be generated over a broad range of operating speeds. Its operation is as follows: A variable-speed electric motor turns the "driving" shaft which carries a 60-tooth gear to generate readout of shaft speed in revolutions per minute (RPM) and a 5.9 kg (13 lb) flywheel to provide large angular inertia and thus assure essentially constant angular velocity of this driving shaft. The driving shaft is connected to a "driven" shaft by means of a Hooke's, or universal, joint. This driven shaft is fitted with a "test" flywheel (with small inertia) made of lightweight foam plastic material. The heavy constant-speed flywheel has a circumference of 30.5cm (12 in), while the lightweight test flywheel is 61cm (24 in) in circumference.

Bench experiments are conducted by using the instrumentation to measure ICAV of the test flywheel as the rotational speed and the angle of the Hooke's joint are varied. The ICAV undergoes a sinusoidal variation twice each rotation, the magnitude of which depends predictably on the angle of "bend" in the Hooke's joint. Ladder tapes of alternate light and dark stripes are installed on the circumference of both flywheels, and these tapes are scanned by an optical pickup sensor. A precision shaft encoder, capable of producing 900 cycles of square wave per revolution, is attached to the driven shaft near the test flywheel. The shaft encoder and the ladder tape/optical scanner systems both operate on the same principle: there is a direct proportionality between the frequency of their electrical outputs and shaft angular velocity. The angle between the driven and the driving shaft (through the Hooke's joint) is calibrated in terms of the so-called K-factor, defined as

$$K = \frac{ICAV_{max} - ICAV_{min}}{ICAV_{average}} ,$$

thus utilizing the mechanical property of the Hooke's joint which specifies that if there is a known angle between the two shafts to which the joint is attached, the motion of the output shaft will vary from the motion of the input shaft in a predictable manner. The angular velocity of the output shaft during each rotation of the input shaft undergoes a variation that can be accurately calculated[6].

As anticipated, initial tests performed with the bench rig verified that the precision optical shaft encoder generates extremely "clean" ICAV

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[6] Doty, V., and W. James, Elements of Mechanism, Wiley & Sons, 1954.

signals. For this reason, the shaft encoder was used as the standard against which other measurement techniques were compared. This device (Model 30G900IDZPA1A, manufactured by Sequential Information Systems, Inc.) is ordinarily used in the direct mode where it produces 900 square wave cycles per revolution. The shaft encoder was used on the Enterprise test engine at SwRI (Section 5.1) during preliminary development work and also on test engines at the ALCO and Fairbanks Morse manufacturing plants (Sections 5.3 and 5.4). All three of these engines were coupled to alternators, and special adapters were fabricated to allow attachment of the shaft encoder to the rear of the alternator shaft. The difficulty (or outright impossibility) of satisfactorily attaching a shaft encoder to actual ship engines in the field necessitated development of a practical alternate angular velocity sensing means, and this situation resulted in development of the optical scanner system using ladder tapes which was alluded to earlier in the description of the bench test rig.

The optical scanner system operates in the following manner. Adhesive-backed tape with alternate light and dark stripes is attached to the rim of the flywheel of the test engine. A small light source in the scanner illuminates a region of the tape (smaller than an individual stripe), and a photo-transistor senses reflected light from the illuminated tape markings as they pass and produces an output signal whose frequency is proportional to angular velocity, just as the shaft encoder does. Thus, output frequency of either system is directly proportional to instantaneous rotational speed. The optical scanner/ladder tape arrangement is equivalent to what is done inside the shaft encoder, but it is not quite as precise due to manufacturing variations in the spacing between and width of the tape marks. Bench tests have established that under average conditions the optical scanner can, with the available ladder tape, resolve K-factors in the range of 0.004 to 0.006. This resolution is two or three times poorer than that obtained with the shaft encoder, but it is considered satisfactory for most diagnostic purposes. More precise ladder tape can be fabricated if the need arises.

Flywheel rotation may also be sensed using the flywheel ring gear teeth and either a magnetic pickup or the optical sensing method described above. In the latter case the optical system illuminates and scans these teeth just as it does the ladder tape marks, and thereby produces a signal which is essentially the same as described previously. As a matter of completeness, ICAV recordings were made using the optical pickup to sense the flywheel teeth on some test engines. However, this work confirmed our suspicion that this is not a particularly satisfactory way to derive ICAV signals since the ring gear provides poor resolution (too few teeth) and, hence, is not precise enough for diagnostic purposes.

A small amount of time and effort was also expended at the bench to verify that ultrasonic doppler is a promising means of obtaining the ICAV signal from a rotating member. With this technique, a beam of ultrasound is directed more or less tangentially toward the edge of the test wheel. The

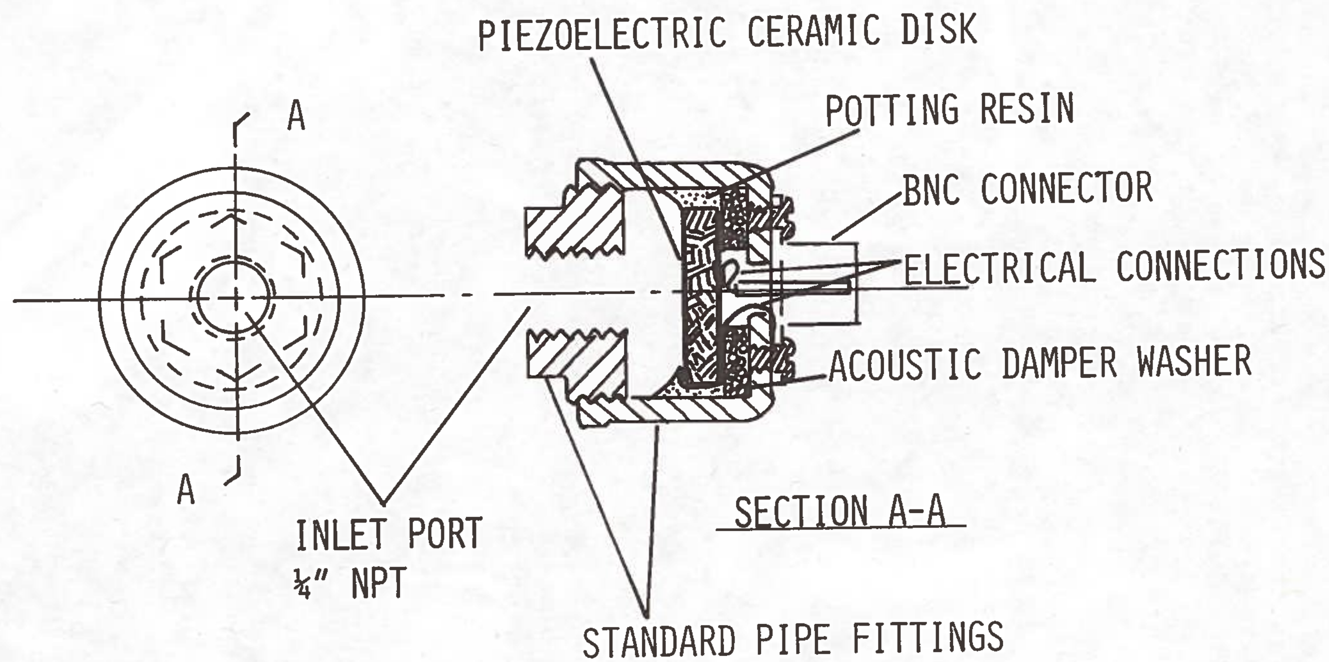


FIGURE 4.2 - PIEZOELECTRIC TRANSDUCER FOR MEASUREMENT OF DYNAMIC CRANKCASE PRESSURE

for direct real-time chart recording. The data shown in later sections (5.1 and 5.2) were obtained this way. This method was at best marginally satisfactory since we often needed to analyze ICAV harmonic components with frequencies at or beyond the response frequency of the galvanometer. For subsequent tests, data were recorded on magnetic tapes at 38 cm/sec (15 in/sec) and then played back onto the strip chart recorder at 2.4 cm/sec (15/16 in/sec). This 16:1 speed reduction lowered signal frequencies by the same ratio and therefore allowed a conventional strip chart recorder to accurately reproduce the waveforms. This process resulted in much better hard-copy records and appeared to be the only practical method for use in any field-worthy prototype diagnostic system that might be developed.

In all cases, signals were monitored on a conventional oscilloscope during the various test series.

4.5 Prototype Diagnostic Hardware

4.5.1 Diagnostic System Mk I

Figure 4.4 is a block diagram of this ICAV detector, which was used during ICAV tests with the bench rig, the Enterprise engine at SwRI, and the DURABLE's ALCO engine. The complete schematic diagram of the Mk I system is contained in Appendix A for reference purposes. The detector was designed to operate in two test modes, as described in the following paragraphs.

Consider the first operating mode (solid lines) in which the optical sensing head "reads" a ladder tape that is illuminated by a suitable light source. Passage of the light and dark stripes is sensed by a photo-transistor (type MRD300) whose output feeds into a 100X (one hundred times) amplifier, then to a zero crossing detector whose square wave output goes to a phase detector which is part of a phase locked loop (PLL) system. The output of the phase detector is an electrical (error) signal whose amplitude is proportional to the phase difference between the ladder-tape derived input signal and the voltage controlled oscillator (VCO) output. After suitable filtering, this error signal is in turn used to control the frequency of the VCO, thereby closing the control loop. The VCO is then forced to exactly track the ladder tape signal, and the error voltage that forces the VCO to follow the frequency excursions of the input signal (around some average value) is the ICAV signal.

We are employing here a simple and very sensitive method of frequency modulation (FM) detection, and the integrated circuits (IC) employed are of the same type found in current FM receivers. Note that the PLL detection system described above produces an output signal only when crankshaft angular velocity (and, therefore, the tape scanner output frequency) varies about its constant speed value at a rate which produces electrical signals that can pass through the PLL feedback circuit filter. Since this filter is of low pass configuration, the PLL will track (and produce a signal output for) low rate (frequency) ICAV, but not for higher frequency noise components which are of no interest. The VCO and zero crossing detector outputs are fed into a separate circuit designed to give indication (lighted LED lamp) of when the PLL is locked onto the ladder tape input signal.

The second operating mode of the Mk I detector is shown with dotted lines on Figure 4.4. Leads marked 1 and 2 in the figure are removed when it is desired that the unit function with the output from the shaft encoder instead of that from the optical pickup and ladder tape. The sine wave output of the shaft encoder is fed to the zero crossing detector and the PLL directly; otherwise, the system functions as already described.

4.5.2 Diagnostic System Mk II

Tests conducted on board the DURABLE disclosed the need for more flexibility in the field test equipment and, in response to this need, a redesign of the electronic circuitry was undertaken. A schematic of the Mk II is in Appendix B. This unit has been found to be entirely satisfactory, and we believe the circuit techniques embodied in this design are generally suitable for use in later generations of diagnostic equipment.

As a first step, several new PLL circuits were evaluated, and it was decided to switch to RCA type CD 4046. This PLL IC is unusual in that it has two built-in phase detectors; one is a special type employing edge-triggered logic which provides an extremely wide locking range; the other is a more conventional low-noise type. The Mk II test unit can thus provide two varieties of PLL ICAV detection and, in addition, is capable of ICAV detection by means of direct time integration of the pulses out of either the shaft encoder or the optical scanner. Time integration detection is the method most frequently employed in the past, both in our ICAV work and in commercial torsional analysis equipment. It is simple and direct, but rather insensitive, and it suffers from a much poorer single-to-noise ratio (S/N) than the PLL scheme. The Mk II also incorporates signal conditioning circuitry for deriving the SYNCH signal from the transducer attached to a selected injection line. In addition, more flexibility was built into the Mk II regarding available amplifier gain and its control.

Figure 4.5 shows in block diagram form the general functions and switching provisions of Mk II. Referring to the figure, it can be seen that ICAV may be sensed using ladder tape or gear teeth with the optical scanner, or it can use the shaft encoder. The same amplifier which is used with these sensors may also be used as a preamplifier for the PKD transducer. This amplifier output can be switched through an adjustable filter and then back through the variable-gain signal amplifier for PKD presentation, or it can be fed into a zero crossing detector to produce a signal suitable for ICAV detection. The zero crossing detector output may be switched to the PLL circuit or to the time integrator ($T\Sigma$) as desired. In the PLL mode, either of the two phase detection methods may be switched in for comparison. An indicator lamp shows when the circuit is locked to the input signal. An input switch for the adjustable filter circuit allows selection of PKD (as mentioned above), PLL output, or the output of the time integrator circuit for ICAV presentation. After filtering, the signal goes to a variable-gain signal amplifier before appearing at the output connector. Signal conditioning for the data synchronization (SYNCH) signal incorporated into Mk II is as shown in the block diagram.

5. ENGINE DIAGNOSTICS TEST PROGRAM

5.1 Enterprise Engine at SwRI

5.1.1 Test Procedures

This engine is an eight-cylinder, four-stroke cycle, in-line unit with firing order 1-4-7-3-8-5-2-6. The third cylinder in the order (No. 7) was modified so that the injector pump fuel rack could be controlled independently of the engine governor setting. In the discussion of test data for this engine, as well as all others, "normal fuel" indicates the normal injector rack position for a particular engine speed, "low fuel" (or "underfuel") indicates a reduced rack setting, and "excess fuel" (or "overfuel") means that the controlled cylinder rack setting was increased until a slight engine knock was heard. No attempt was made to determine exactly what underfuel and overfuel meant in terms of percentage cylinder power imbalance since there was no provision for loading this engine. Under no-load conditions, ICAV variations induced by fuel changes in one cylinder are very small; hence, the Enterprise was considered to be a "worst case" engine. Therefore, it was thought that instrumentation capable of resolving ICAV waveform differences in this situation should be sensitive enough to work satisfactorily with almost any other large engine.

Piezoelectric pressure transducers were installed to obtain baseline (normal) PKD data and also No. 1 cylinder firing pressure for use as a mark for data synchronization. As described elsewhere, this synchronization was obtained more easily in later tests by sensing the injection event directly off the high-pressure injection line of the selected cylinder.

5.1.2 Data Analysis

Tests conducted with this engine produced chart recordings of ICAV data under both normal and abnormal fueling conditions as shown in Figure 5.1. The quality of the original chart recordings is rather poor. In order to make the traces more legible for reproduction, portions of them were carefully traced over to clarify the features being described. However, the data shown are faithful, hard-copy representations of real-time signals observed during the tests.

The traces shown in Figure 5.1 illustrate the effect on ICAV of cylinder power imbalance caused by fueling variations. Different degrees of electrical filtering were used as noted to show that effect on the observed ICAV frequency spectrum. At an engine speed of 240 RPM (Traces 1 to 9, inclusive), it is easily seen that the ICAV signal is optimized when the filter bandpass is set to the 5 Hz to 40 Hz range (Traces 4 to 6). The signal obtained with a filter bandpass of 5 Hz to 65 Hz (Traces 1 to 3) is slightly degraded by the higher-frequency components that are passed by the filter. This degradation is even more evident in Traces 7 to 9, where the upper bandpass limit was increased to 350 Hz. These examples illustrate the importance of optimum ICAV signal filtering. At an engine speed of 900 RPM (Traces 10 to 12), the higher-frequency ICAV signal does not lend itself to ready interpretation due both to the limited frequency response of the direct-writing chart recorder and to the fact that only very small variations in ICAV are present at the higher engine speed. Chart recorder presentation can be upgraded, but it is our opinion that high-(engine) speed ICAV is, for several reasons, inherently less reliable for diagnostic purposes than that obtained at lower speeds. These points are discussed in somewhat greater detail in later sections of this report.

Figure 5.2 illustrates real-time dynamic crankcase pressure (PKD) recorded directly from the piezoelectric pressure transducer connected to the engine crankcase. No <u>known</u> engine defects were present when this signal was recorded. It can be seen that the dynamic pressure variation is small, regular, and has the form of two pressure pulses per cylinder firing event. These pressure variations are the result of changing crankcase volume which accompanies normal piston motion during crankshaft rotation. It appears that use of this waveform would be limited to detecting only gross changes in PKD.

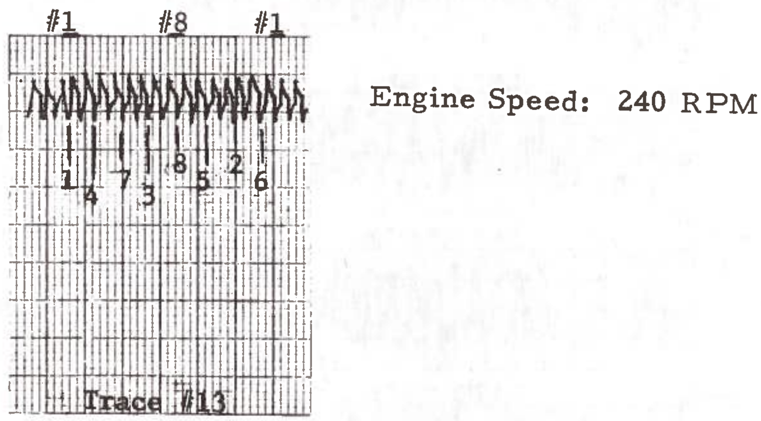


FIGURE 5.2 - ENTERPRISE ENGINE DYNAMIC CRANKCASE PRESSURE RECORDED WAVEFORM

The preceding ICAV data were obtained using the optical shaft encoder and the Mk I detector. Later, after satisfactory development of the simplified ladder tape sensing technique and construction of the Mk II detector, baseline ICAV data were once again obtained from the Enterprise engine under normal operating conditions. Figure 5.3 contains these data, which illustrate once again the pronounced effect filtering has on ICAV signals. The ICAV signal fundamental was at 30 Hz (450 RPM/60 x 4 cylinders firing each revolution). The upper filter rolloff frequency was increased in steps with engine speed held constant, and a trace was recorded at each setting of the filter bandpass. Immediately after Traces 5, 7, and 8 were made, a photograph of the monitor oscilloscope trace was taken for comparison purposes (Figure 5.4). The two sets of traces generally contain the same information, but the oscilloscope shows greater detail in the form of high frequency components. The chart recorder frequency response begins to fall off rapidly at about 100 Hz, and this effect can be seen by comparing the photographs with the chart traces when the filter bandpass is widened. It was beyond the scope of this work to attempt to determine the diagnostic significance (if any) of these higher frequency components.

5.1.3 Conclusions

We conclude from these tests that:

- ICAV can provide diagnostic information related to cylinder power imbalance when applied to engines of the same type as the Enterprise test engine.

- The ladder tape/optical sensor offers a practical means of deriving ICAV signals from large diesel engines which cannot accommodate a shaft encoder.

- PKD was not pursued past baseline data since defects could not be induced in the Enterprise engine that would influence PKD; however, we may conclude that its PKD waveform was of the type expected.

5.2 ALCO 16V 251B Engine Onboard USCGC DURABLE (WMEC 628)

5.2.1 Test Procedures

This series of tests of the ICAV and PKD prototype instrumentation was conducted on-board the medium-endurance cutter (MEC) DURABLE in Brownsville, Texas. This vessel is powered by two 16-cylinder ALCO 251B diesel engines, each rated 2500 Hp at 1200 RPM. The engines rotate in opposite directions and have different firing orders (Appendix C). The purpose of these tests was to (1) gain experience in use of the diagnostic techniques with an in-service Coast Guard engine, (2) obtain ICAV data from an engine that could be operated under at least a slight load.

The tests were conducted during a two and one-half day period. First, an SwRI technician set up the prototype instrumentation and readout devices (strip chart recorder and oscilloscope), laid a piece of dual-track ladder tape around the perimeter of the port engine flywheel, installed the PKD pressure transducer in the oil dipstick tube, and installed a clamp-on type pressure transducer on the No. 1 cylinder injection line for SYNCH. The engine was then operated briefly to determine that all instrumentation components were functioning properly.

5.2.2 Data Analysis

This on-board demonstration presented several potential problems that were detailed in a letter to the Technical Contract Monitor at TSC. Briefly, the points of concern involved the short time available to optimize the instrumentation for use on the ALCO engine (at that time an unknown entity), the fact that there would be limited means available to induce or simulate engine malfunctions and, finally, lack of knowledge about the mechanical condition of the engine.

In retrospect, it can be said that only the latter point had a significant bearing on the results of these tests. The instrumentation was readily adapted to the engine, and signal response was judged to be adequate for evaluation. We were able to induce an underfuel or overfuel condition in individual cylinders by means of a simple manipulation of the appropriate injector racks, and this technique was helpful in evaluating the ICAV measurement. However, no means was available to induce crankcase blowby conditions required for a true test of the PKD measurement. The third problem mentioned above--namely, the lack of knowledge concerning the baseline engine condition--was the most serious obstacle. This statement will be borne out in the data analysis that follows, where difficulties were encountered in trying to decide whether an observed signal artifact represented an engine malfunction (already present) or an anomaly in the signal produced by the instrumentation itself.

In any case, the various tests for record were accomplished. The keys to the test conditions are given in Table 5.1 and are explained as follows. Twenty-four runs were conducted. Engine speed for most of these tests was 435 RPM; three tests were conducted at 700 RPM. The engine was operated at both speeds with the clutch disengaged (an essentially unloaded operating condition) and at the lower speed with the clutch engaged and approximately two feet of propeller pitch applied (slight load). Higher engine loads at 435 RPM, and operation under any load at 700 RPM, were precluded by the fact that the cutter was tied up at the dock, and such operation under these static conditions was deemed inadvisable by ship's engineering staff.

Initial tests were performed with the ICAV optical scanner using each of the two ladder tape tracks and also the ring gear teeth on the flywheel. One tape track had alternating dark and light bands, each 1.27mm (0.05 in) wide. The space between leading edges of adjacent dark bands was therefore 2.5mm (0.1 in), and this tape is referred to as the narrow track. The second tape also had dark bands of 1.27mm (0.05 in) width, but they were separated by 3.8mm (0.15 in); the distance between leading edges of consecutive dark bands was therefore 5.1mm (0.2 in), and this tape is referred to as the wide track. The narrow band track thus has 394 dark stripes per meter (10 per in), while the wide band track has one-half as many.

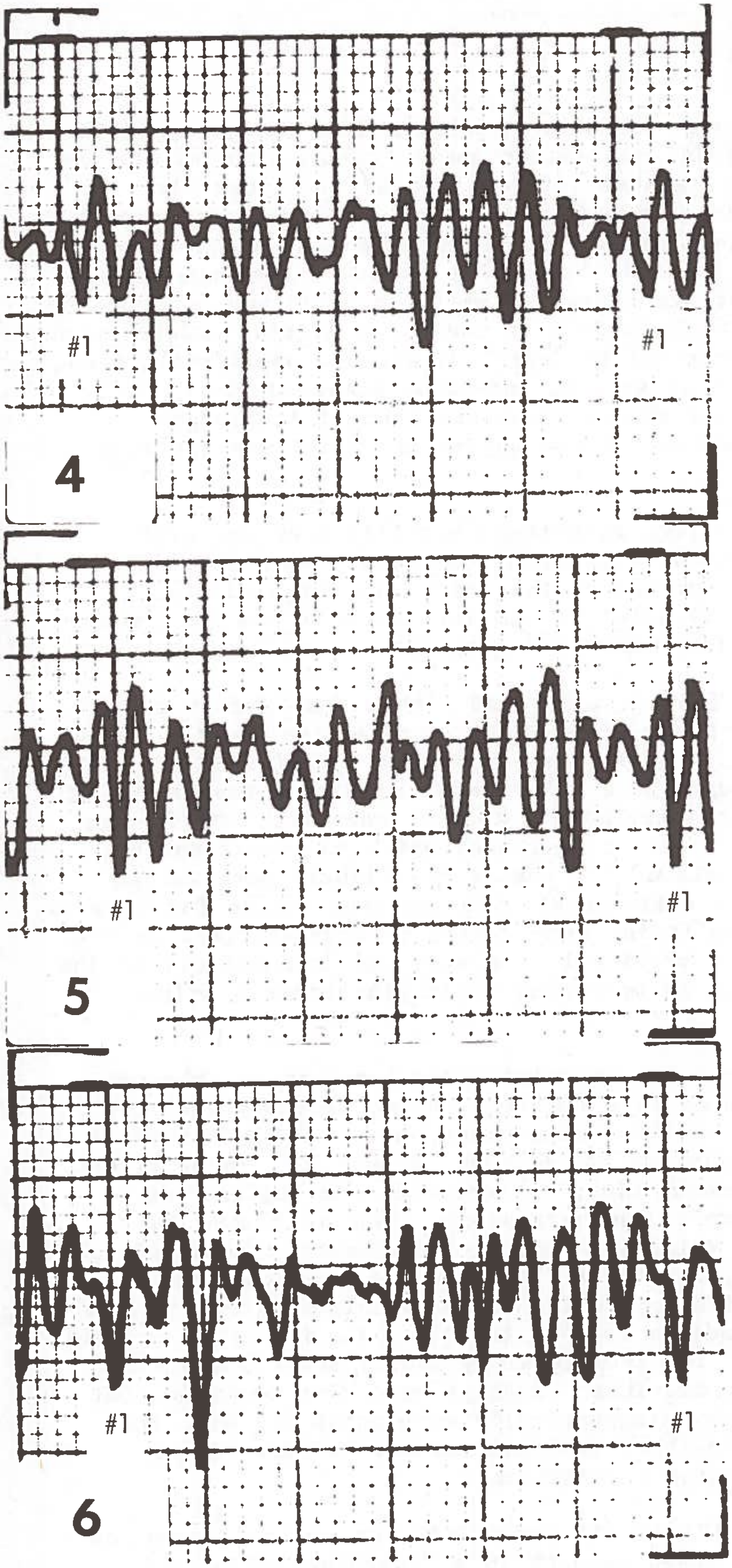
The ALCO 251 flywheel circumference is approximately 4.1 meters (13.5 ft), so the total number of dark stripes around the flywheel perimeter was 1620 and 810, respectively, for the two tape tracks. By way of comparison, there were approximately 300 ring gear teeth on the flywheel, and the optical shaft encoder used in tests at SwRI produced 900 pulses per revolution. Therefore, each of the tape tracks in principle has a potential resolution equal to or greater than that of the shaft encoder, all other factors being equal. These comments also apply to ALCO and Fairbanks Morse engines used in later tests except that some did not have ring gear teeth on their flywheels.

Filter bandpass width for the ICAV signal was optimized for each test condition and, as it turned out, the only major change in the bandpass was necessitated by the high speed (700 RPM) tests. Tests were conducted at baseline (normal) conditions and with overfuel and underfuel conditions in two cylinders (though not at the same time). These two cylinders were Nos. 5 and 8 on the left (L) engine bank, and they occur as Nos. 12 and 10 in the firing order, respectively.

The strip chart traces recorded real-time were somewhat faint, with individual peaks close together due to the relatively slow chart speed available (about 10 cm per second). In order to facilitate interpretation of these traces, a single firing order cycle (obtained over two engine revolutions) of the waveform was selected for enhancement and enlargement. The enhancement again consisted of carefully tracing over the waveform with a fine-point pencil, and then these enhanced traces were enlarged photographically. The traces were not substantially altered by this process. Two further aids to interpretation were added to these reproductions. First, the pressure impulse from the No. 1 cylinder injection event was recorded as a horizontal dash at the top of each chart. This SYNCH mark was used to locate the ICAV peak for the No. 1 cylinder, and this peak has been so labeled at the beginning and end of each cycle on the traces. Second, for those tests where an abnormal fueling condition was induced, the cylinder so affected has been indicated.

Figures 5.5 and 5.6 (Traces 1 to 6) compare baseline ICAV signals from the two tape tracks and the ring gear teeth with the engine in loaded and unloaded operating modes, respectively, at 435 RPM. As expected, the signal produced by the two reflecting tapes is superior to that obtained by reflecting the light beam off the ring gear teeth. Upon examination it appears that, for reasons unknown, the waveform obtained by use of the wide tape track offers slightly more detail than does that from the narrow track. However, it was decided at the time that the narrow track should be used for all subsequent tests since it produced the greatest number of reflections per revolution and should (theoretically) give superior resolution to the waveform.

Comparing individual cylinder impulses (flywheel acceleration is toward the bottom of the chart) in these traces, it can be seen that those made with the engine under load are more regular and of slightly greater

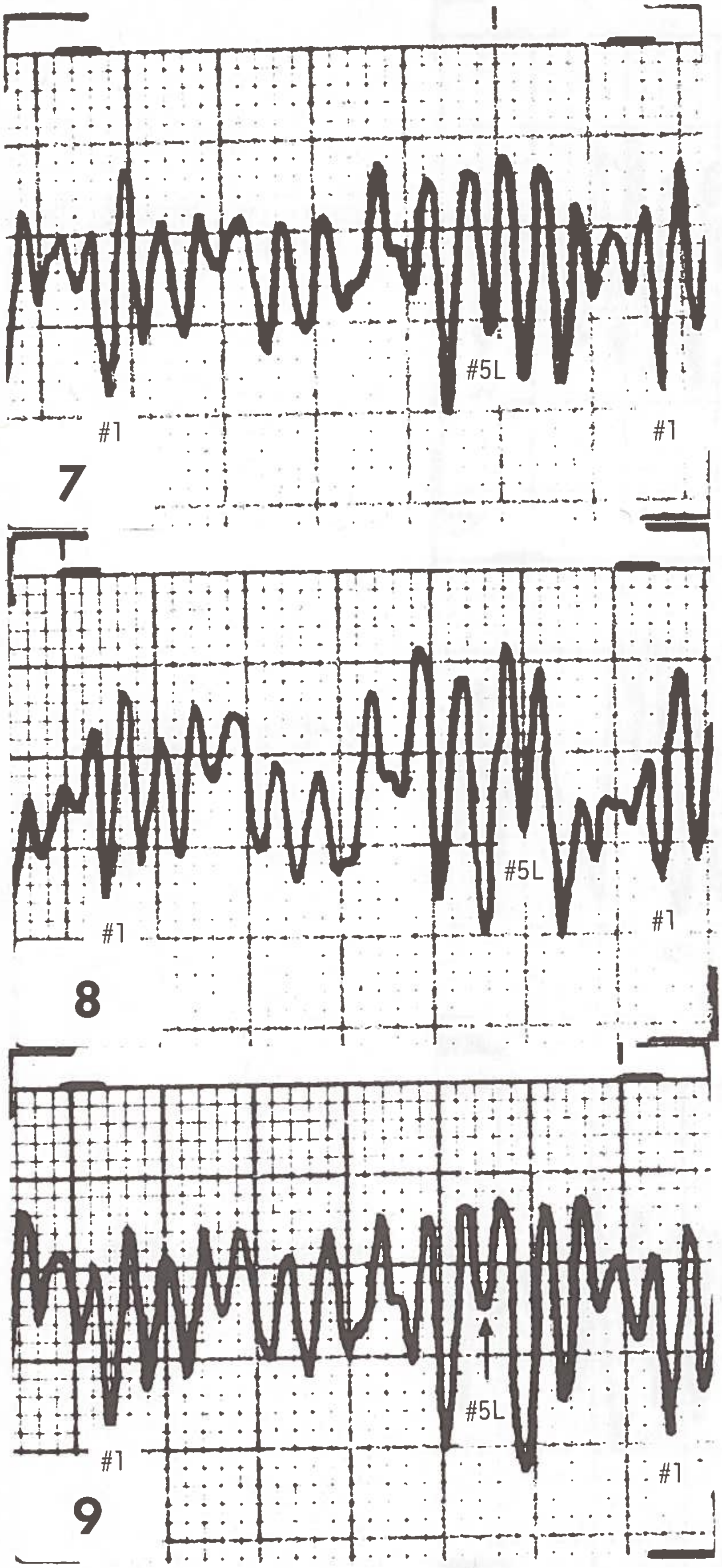


Narrow Optical Track Tape,
16-85 Hz Bandpass

Wide Optical Track Tape,
16-85 Hz Bandpass

Ring Gear Teeth,
16-85 Hz Bandpass

FIGURE 5.6 - ICAV FOR ALCO ENGINE IN MEC DURABLE,
NO-LOAD OPERATION AT 435 RPM, NO KNOWN ENGINE DEFECTS PRESENT

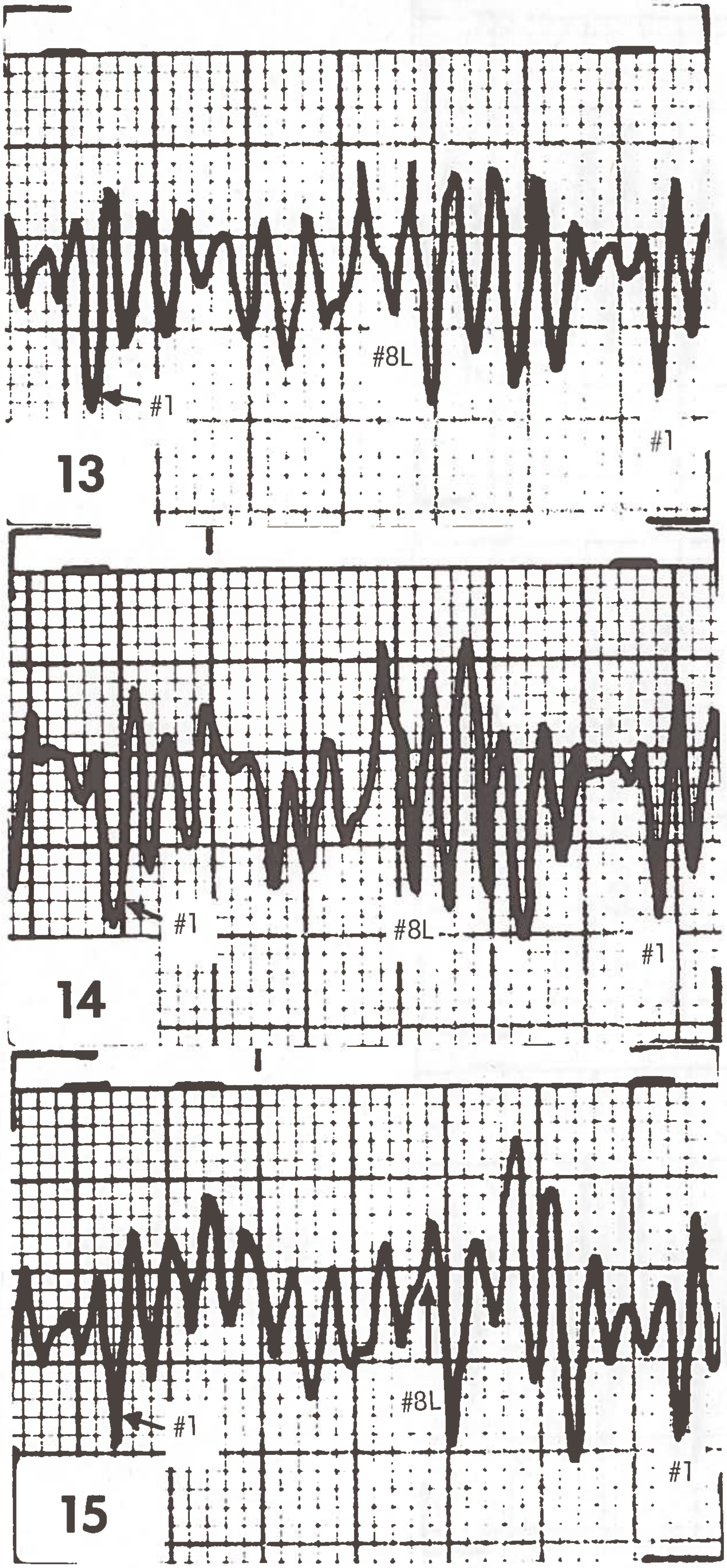


NORMAL FUEL RACK SETTING,
16-85 Hz Bandpass

OVERFUEL CONDITION,
16-86 Hz Bandpass

UNDERFUEL CONDITION,
16-85 Hz Bandpass

FIGURE 5.7 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING IN CYLINDER NO. 5L, UNDER LOAD AT 435 RPM

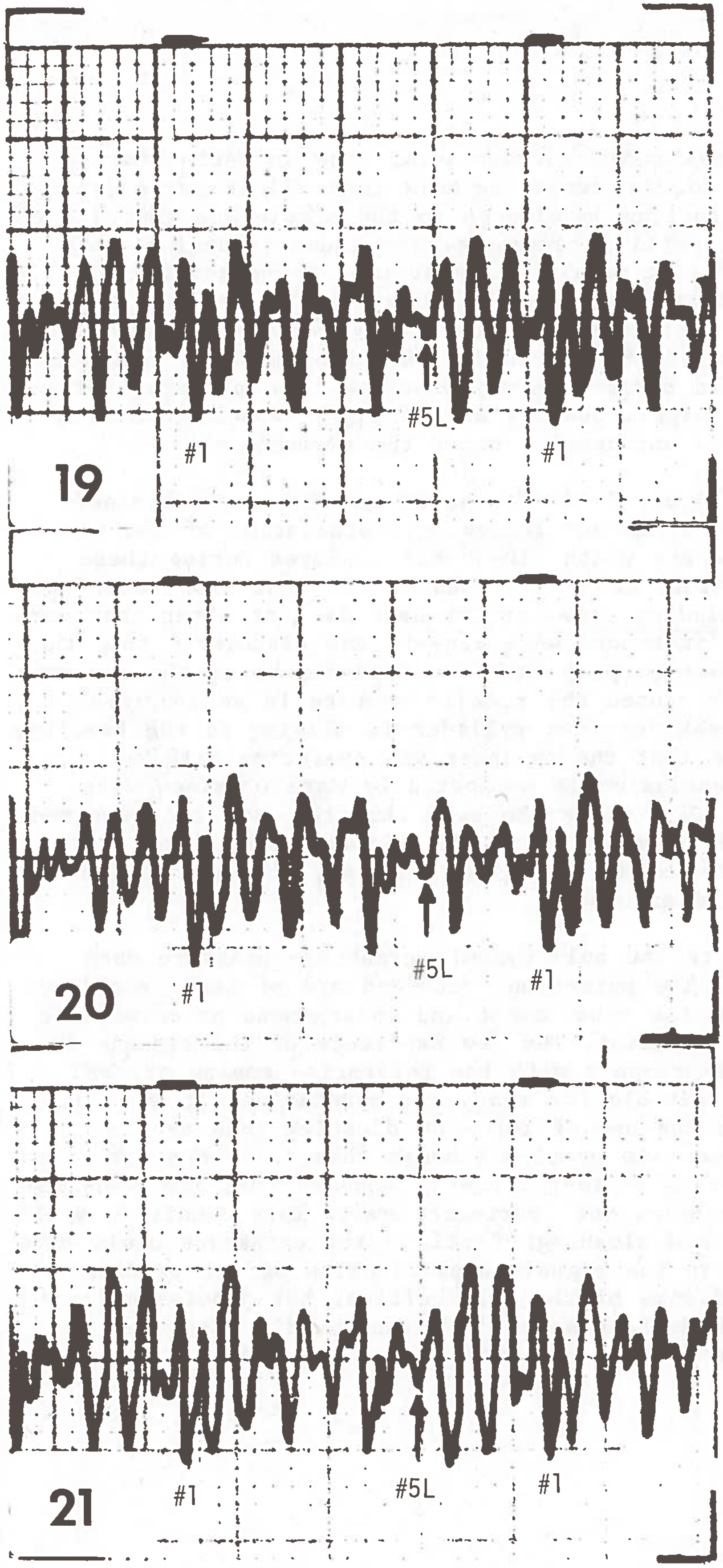


NORMAL FUEL RACK SETTING,
16-85 Hz Bandpass

OVERFUEL CONDITION,
16-85 Hz Bandpass

UNDERFUEL CONDITION,
16-85 Hz Bandpass

FIGURE 5.9 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING IN CYLINDER NO. 8L, UNDER LOAD AT 435 RPM



NORMAL FUEL RACK SETTING,
75-110 Hz Bandpass

OVERFUEL CONDITION,
75-110 Hz Bandpass

UNDERFUEL CONDITION,
75-110 Hz Bandpass

FIGURE 5.11 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING IN CYLINDER NO. 5L, NO-LOAD OPERATION AT 700 RPM

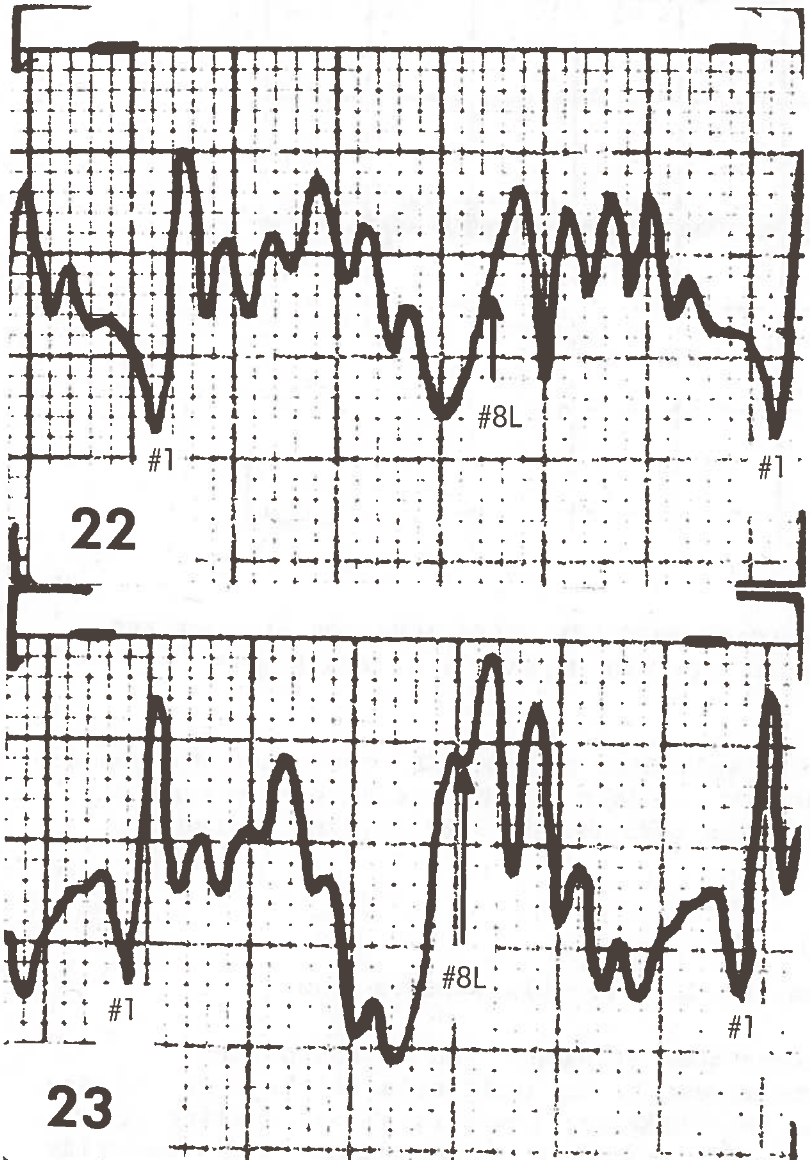


FIGURE 5.12 - ICAV FOR ALCO ENGINE IN MEC DURABLE WITH ABNORMAL FUELING (LOOSE RACK) IN CYLINDER NO. 8L, NO-LOAD OPERATION AT 435 RPM

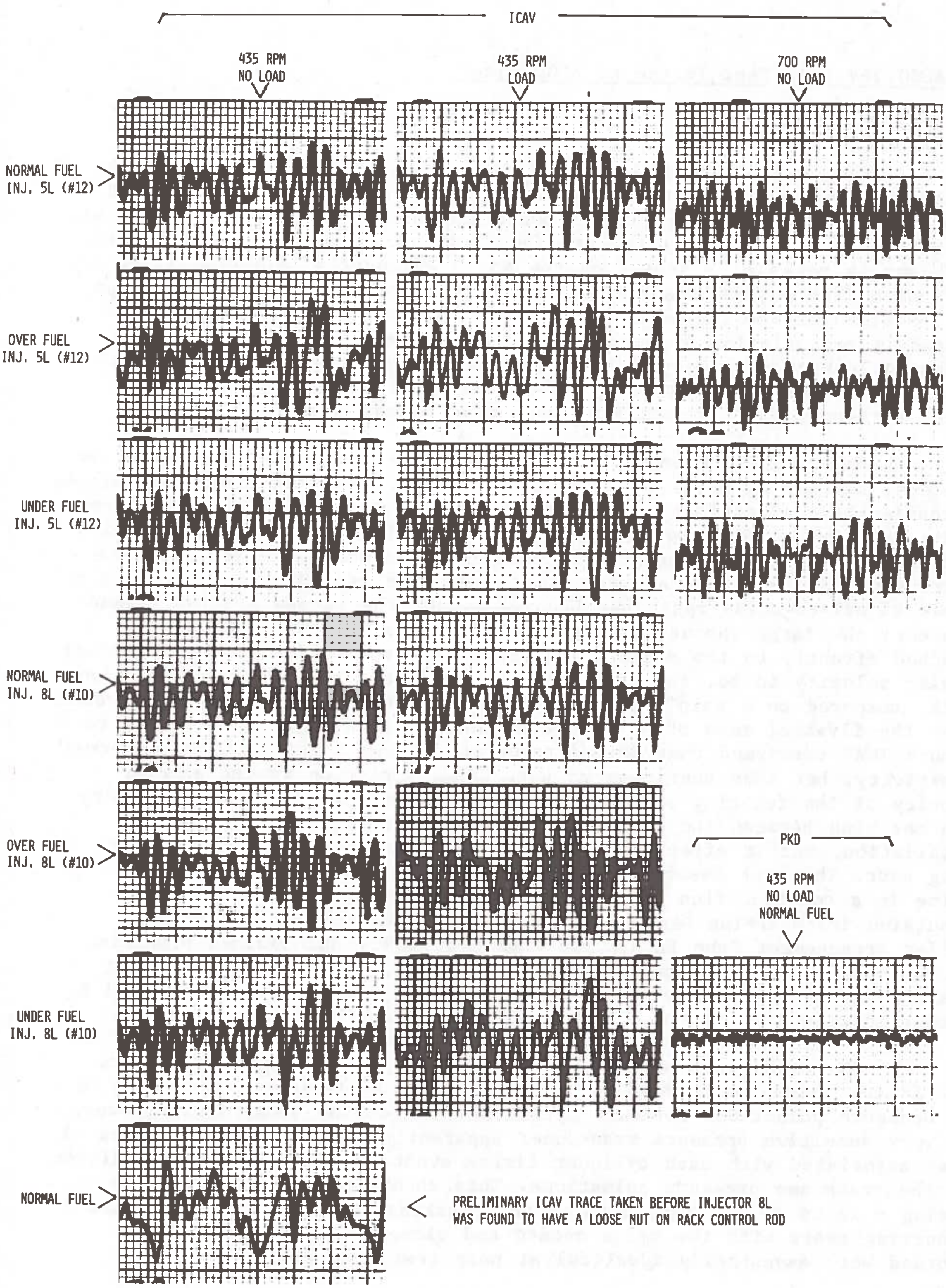


FIGURE 5.14 - DATA MATRIX FOR ALCO 16V 251B (STARBOARD) ENGINE
USCGC DURABLE (WMEC 628)

Even though the calibration and baseline data runs had disclosed the difficulties enumerated above, it was decided to obtain data for record with induced leakage defects as noted above and see if careful analysis would yield answers which would be of benefit in later test work.

5.3.2 Data Analysis

The ICAV and PKD obtained in these tests were not of usable quality for the reasons given above. However, a careful review of all instrumentation and procedures employed in the test program at ALCO was conducted to determine if any steps could be taken to help ensure success of the next scheduled series of tests at Fairbanks Morse since that engine was configured much the same as the ALCO.

It was concluded that the Mk II ICAV instrument was sensitive enough to measure ICAV under normal circumstances since the earlier Mk I instrument was able to detect ICAV during the test program conducted on the medium-endurance cutter DURABLE, yet the Mk II had demonstrated by comparison better dynamic range and sensitivity than Mk I. Thus, the configuration encountered with the ALCO test engine described above was indeed the reason that the ICAV signal proved too weak for diagnostic use. The same difficulties were now anticipated for the upcoming test series with the Fairbanks Morse test bed engine, which is discussed in the following section.

Even though instrumentation had been shown adequate to measure ICAV of a shipboard installation, it was apparent that an extensive instrument redesign effort would be required to increase sensitivity to the point where the very low-level ICAV signals produced by these non-propulsion (test bed) engines could be detected, and even then the signals would require further processing to be useful. Such an effort was outside project objectives.

The dynamic crankcase pressure data recorded as hard-copy during the tests revealed that pressure pulsations due to blowby from a known defect could not be detected by inspection of the traces. This meant that either significant blowby was not produced by the simulated malfunction in one cylinder or that the pressure pulsations, though present, were damped or masked so as not to appear in the recorded signal. The least desirable situation would be that the pressure pulsations were indeed present, but were not seen by the transducer. We therefore analyzed this possibility.

It was speculated that the pressure pulsations might have been damped by the crankcase baffles used to reduce oil splash since the transducer pressure port was several feet away from the cylinder with the induced defect. But to be a practical diagnostic measurement, the transducer must pick up pulsations from any cylinder, regardless of its proximity to the pressure port; otherwise, a transducer would have to be installed near each cylinder or pair of cylinders, an impractical solution from the standpoint of quick transducer installation and data acquisition.

condition) and, hence, to obtain a better definition of the relationship between a known induced malfunction and the resulting change in the ICAV signal. If variations in flywheel angular velocity of the FM engine, when sensed by ladder tape and scanner, turned out to be so small as to escape detection, then the major objective of the test bed work would still remain unfulfilled, and it was not thought that acquisition of ICAV data from another type of transducer (the shaft encoder) located on a different part of the engine would help to salvage the situation. The only reason for attempting to obtain ICAV data with the shaft encoder was to use these data as a reference or bench mark for comparison with data obtained by the ladder tape/scanner technique since, theoretically, the shaft encoder should offer slightly superior resolution. Otherwise, test procedures were essentially the same as those used at the ALCO plant.

Due to its design, which features cylinder liners with ports at both ends, PKD defects cannot be induced into the FM opposed-piston engine short of actually perforating a piston. The ports allow pressure pulsations from piston ring leakage to enter either the intake air receiver or the exhaust manifold, but not the upper or lower crankcase.

5.4.2 Data Analysis

The FM engine produced ICAV signals which were just barely identifiable as belonging to a specified cylinder. They were, however, like the factory ALCO data, i.e., much too poor in quality to consider for diagnostic use. Therefore, they are not reproduced here. The reasons for this condition were, again, too much rotating mass attached to the engine and no way to declutch the alternator to reduce this mass.

5.4.3 Conclusions

From these tests we conclude that:

- Large diesel engines in this configuration cannot be diagnosed with ICAV, and the same considerations apply as in the case of the factory ALCO tests described in the previous section.

- PKD can only respond to holes in a piston. Leakage past the rings goes into either the exhaust manifold or the air box, and not into the crankcase; pressure pulses cannot, therefore, be detected with the engine geometry of the FM opposed-piston power plant. Implementing an artificial defect of this type was considered too dangerous to attempt in light of its limited relationship to defects that actually occur.

As part of the trip to FM a visit was made to the U.S. Navy Propulsion Engineering School at Great Lakes, Illinois. We had been advised that this facility had both ALCO 16-251 (turbocharged) and Fairbanks Morse 38D8-1/8 (non-turbocharged) test bed engines connected to water brake dynamometers, and this proved to be true. This was potentially a much more

TABLE 5.2 - DIAGNOSTIC EVALUATION OF ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER

f_oICAV = 2/15 RPM

PROJECT: 11-4132-005
DATE: 7/19/78

Test Seq.	RPM	f_oICAV	Filter	Gain	Load	Engine Cond.	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
1	400	53	35/85	X100	0	Normal	1	50mV	----	Dyno clutched in at all times & load varied as shown.
2	400	53	35/85	X100	1/2	Normal	2	50mV	----	
3	400	53	35/85	X100	Full	Normal	3	50mV	----	
4	400	53	35/85	X100	0	Under fuel	4	50mV	----	Fuel changed by hand from approx. -80% to 40%.
5	400	53	35/85	X100	0	Over fuel	5	50mV	----	
6	400	53	35/85	X100	1/2	Under fuel	6	50mV	----	Engine has a distinct leaking sound at load.
7	400	53	35/85	X100	1/2	Over fuel	7	50mV	----	
8	400	53	35/85	X100	Full	Under fuel	8	50mV	----	
9	400	53	35/85	X100	Full	Over fuel	9	50mV	----	
10	400	53	35/85	X100	0	Normal	10	50mV	----	
11	400	53	35/85	X100	Full	Normal	11	50mV	----	
12	400	53	35/85	X100	0	Normal	12	0.1V	----	7/10/78 Dyno clutched in 21 (5 in order) and for all fuel .
13	400	53	35/85	X100	1/2	Normal	13	0.1V	----	PKD Transducer on 5L door.
14	600	53	65/140	X100	1/2	Normal	14	0.1V	----	PKD

TABLE 5.2 - DIAGNOSTIC EVALUATION OF ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER (CONT'D)

Test Seq.	RPM	f_oICAV	Filter	Gain	Load	Engine Cond.	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
28	375	N/60 6.6Hz	2/10	X100	0	Under fuel -2mm	28	50mV	----	N/60 Component Turbo not spinning.
29	600	----	65/140	X100	0	Normal	29	0.1V	----	PKD Transducer on 1L door.
30	600	----	65/140	X100	1/2	Normal	30	---	----	
31	600	----	65/140	X100	Full	Normal	31	---	1200-1280	Load dropped off during tape run.
32	600	----	65/140	X100	0	Normal	32	---	1280-1400	
33	400	----	65/140	X100	0	Normal	33	---	1400-1500	
34	400	53	35/85	X100	1/2	Leaking in 2L	34	50mV	Reel 3 000-400	Defective nozzle tip installed in 2L(5) 9X325X1450 ADL-145TM-836-6 Alco Fact.
35	400	N/60 6.6Hz	2/10	X100	1/2	Leaking in 2L	35	50mV	----	
36	400	53	35/85	X100	1/2	Plugged noz. in 2L	36	50mV	400-800	Def. noz. approx. 1/2 holes plugged (2 pics) firing intermittently (in 2L).
37	400	N/60 6.6Hz	2/10	X100	1/2	Plugged noz. in 2L	37	50mV	----	Recording of both 36 & 37 (last few feet shutdown).
38	400	53	35/85	X100	1/2	Eroded tip in 2L	38	50mV	800-1000	Def. Noz. eroded tip 2L(5).
39	400	N/60 6.6Hz	2/10	X100	1/2	Eroded tip in 2L	39	50mV	1000-1130	
40	400	53	35/85	X100	1/2	Normal	40	50mV	1200-1300	Baseline after return to original configuration.
41	400	53	35/85	X100	1/2	Under fuel	41	50mV	1300-1350	6L inj. fuel by hand, 11th in firing order, very bad.

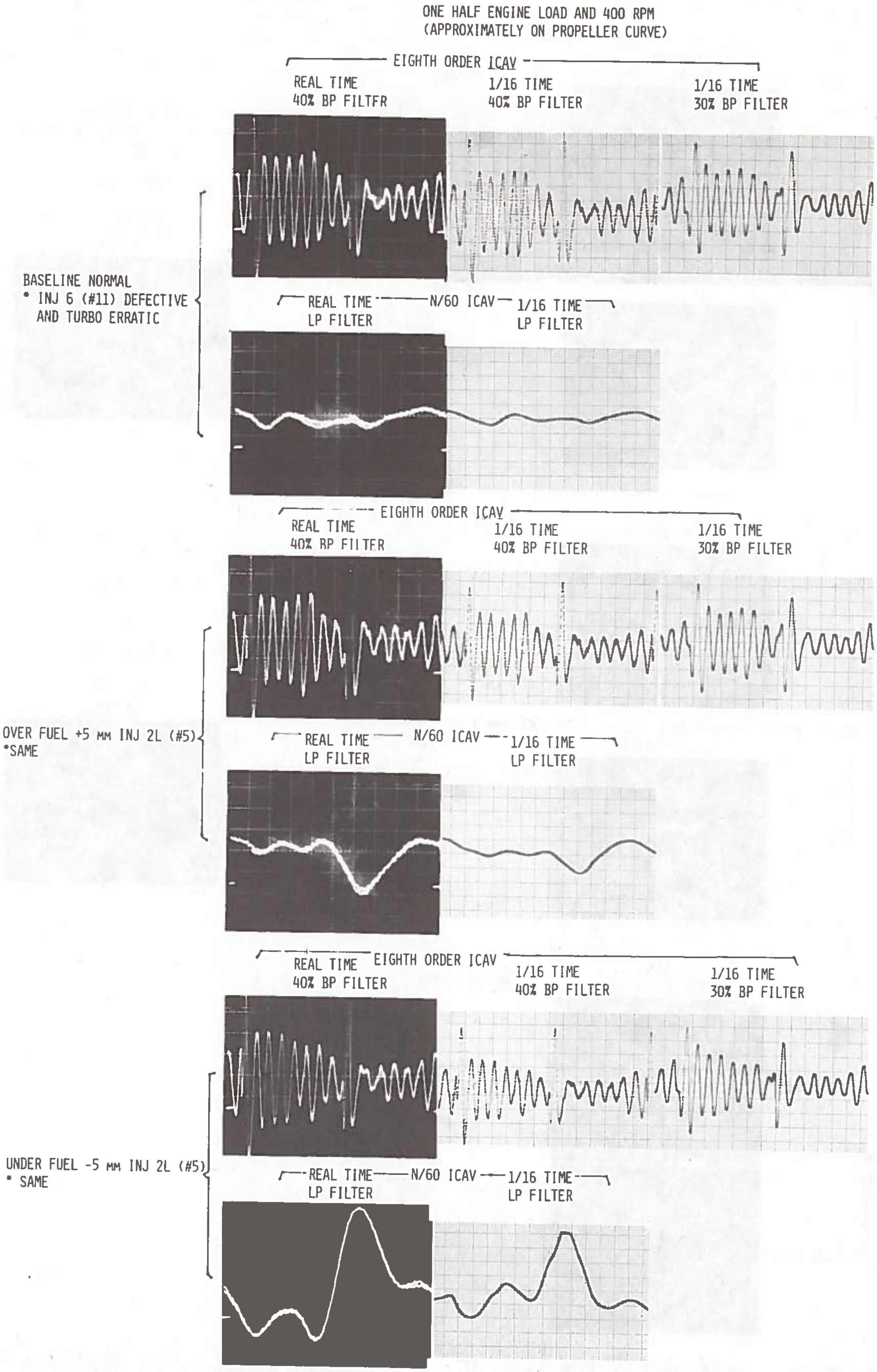


FIGURE 5.15 - DATA MATRIX FOR ALCO 16V-251C, GREAT LAKES NAVAL TRAINING CENTER

traces since the Mk II detector was used. All pertinent information appears in the captions of each figure. The very large excursions in these traces are an artifact of the ladder tape splice and should be ignored.

5.5.3 Conclusion

- Although changes in the ICAV record due to misfueling and the resultant cylinder power imbalance were present, no significant improvement over results of the shipboard tests (the DURABLE series) was shown.

- The PKD waveform was undecipherable due to the presence of a great many pressure pulsations of varying amplitude, shape, and spacing. The unknown mechanical condition of this engine's pistons, rings, and cylinder liners made correlation of these crankcase pressure pulsations impossible.

5.6 Fairbanks Morse 10-Cylinder 38D8-1/8, Great Lakes Naval Training Center

5.6.1 Test Procedures

Test procedures for this engine were unchanged from those described in earlier sections of the report. Fueling defects were introduced by manipulating racks of the two injectors for the target cylinder. This engine was an old model partially modified to ND type (different pistons), but it was still very similar to the engine described in Section 5.4 except for having ten rather than eight cylinders. It was set up for direct reversing, but was operated only in right-hand (normal) rotation. The test sequence is detailed in Table 5.3, following. PKD was not measured for the reasons mentioned previously (Section 5.4.1) relating to the design of the opposed-piston FM engine.

5.6.2 Data Analysis

Figure 5.17 is a montage which illustrates with appropriate captions the principal features of the ICAV data obtained from this engine. The signals are of good quality, and definite waveform changes occur with fueling imbalance in one cylinder. The difficulty is that there appears to be no ready way to interpret the traces in terms of past experience with engines of more conventional geometry (i.e., engines not of opposed-piston design). Notice that the ICAV traces change shape radically as engine speed changes. This effect is surely due to the interplay of the torsional resonances of the engine's two crankshafts and their coupling shaft and gearing. This situation is further complicated by the fact that there is some 12^{o} of angular timing displacement between the two crankshafts (i.e., the two opposed pistons reached their respective TDC positions some 12^{o} out of phase). The mechanical condition of this engine was not known; it may have had power imbalances before known fueling defects were added. We can say with certainty that analysis of ICAV waveforms for engines of this type will be much more complex than for engines of more conventional geometry, such as the ALCO.

TABLE 5.3 - DIAGNOSTIC EVALUATION OF FAIRBANKS MORSE 10-CYLINDER 38D8-1/8, GREAT LAKES NAVAL TRAINING CENTER (CONTINUED)

Test Seq.	Tach* RPM	f_oICAV RPM/6	Filter	Gain	Load	Engine Cond.	Pic.	Scope Vert/ Div.	Mag. Tape Reel /Start/ Stop FTS.	Remarks
14	500	83	60/103	X100	80%	Normal	14	0.2V	600-700	
15	500	83	60/103	X100	80%	Over fuel	15	0.2V	700-800	
16	500	83	60/103	X100	80%	Under fuel	16	0.2V	800-900	
17	500	83	60/103	X100	0	Normal	17	0.2V	900-1000	
18	400	67	47/87	X100	0	Normal	18	0.2V	1000-1100	Baselines
19	300	50	30/70	X100	0	Normal	19	0.2V	1100-1200	

*Tach was not accurate - values from scope timing show that:

300 rpm indicated was 353 rpm
400 rpm indicated was 444 rpm
500 rpm indicated was 531 rpm

ENGINE FIRING ORDERS:

1	2	3	4	5	6	7	8	9	10	
1	6	10	2	4	9	5	3	7	8	RH rotation (normal)
1	8	7	3	5	9	4	2	10	6	LH rotation (reverse)

5.6.3 Conclusions

We conclude from these tests that:

- Torsional resonance ICAV effects in engines of the opposed-piston type are pronounced and very complex. As in other large diesel engines, these effects preclude simple and straightforward analysis of ICAV data for diagnostic purposes.

- Since ICAV changes vs. fueling defects are demonstrated in the data, this means that in principle ICAV is a feasible diagnostic tool for these engines, but one that will require more sophisticated signal processing to yield adequate data interpretation.

5.7 ALCO 16V 251B Engines Onboard USCGC COURAGEOUS (WMEC 622)

5.7.1 Test Procedures

Tests on both main propulsion engines were accomplished during two periods. The diagnostic test equipment and its ancillary devices were set up in a clear space near the aft ends of the engines between their gear boxes. From this location it was possible to conveniently move test sensors back and forth from one engine to the other. ICAV data were first recorded (Part I, Table 5.4) while the cutter was moored at the dock with the engines declutched and unloaded (for later harmonic analysis), and subsequently (Part II, Table 5.4) loaded engine ICAV data were acquired while underway at sea. The only way to measure PKD was by means of the oil dipstick tube, no other openings into the crankcase being available. Since previous tests on the cutter DURABLE had shown this location for the transducer to be unsuitable, we made only cursory measurements to confirm that the same anomalous behavior existed for the PKD data in this case.

A significant change was made in the magnetic tape data recording technique used in these tests in that wide-band (5 Hz to 500 Hz bandpass) signal filtering was used so that when the ICAV signals were later transcribed at lower tape speed as chart traces, narrow-band selective filtering could be employed to select only the ICAV component desired (conventional ICAV, N/60 ICAV, and so on). The COURAGEOUS raw data were thus much more useful than that which had been recorded in earlier tests since that earlier data was band-limited from the start. Identical test procedures were used on both engines except as noted in the following sections.

5.7.2 ALCO 16V 251B (No. 1 Engine, Starboard side, Clockwise/Opposite Rotation)

SYNCH was obtained from the No. 1 cylinder injector line. The rack control on Cylinder 5L (No. 7 in the firing order) was manipulated to provide abnormal fueling conditions.

5.7.2.1 Loaded Engine Data Analysis

The ICAV traces in Figure 5.18 were extracted from the wide-band data recorded from the No. 1 engine while underway at sea and are appropriately marked regarding operating parameters. Inspection of these data reveals that the fueling imbalances produced by manipulating the rack for No. 5L cylinder did indeed produce changes in both the normal and N/60 ICAV record. At the same time, the traces are too irregular to allow simple and straightforward defect analysis even though they were taken at optimum conditions, i.e., with the engine under load. These ICAV records are not of the quality needed to meet the primary program objective of simple interpretation by Coast Guard operating personnel. To be useful, considerable refinement in signal processing and display would be required. The lack of regularity in these ICAV traces is similar to that encountered in the earlier large engine tests and, once again, the difficulties encountered may be attributed to engine operation too near the crankshaft torsional resonance point.

5.7.2.2 Conclusions

These data reinforce the conclusions arrived at in previous tests with ICAV for large diesel engines. They are:

- Cylinder power imbalance very definitely changes the baseline (normal) ICAV record, but the changes are not interpretable in any straightforward manner due to the irregularity of the signals.
- This means that in principle ICAV is a feasible diagnostic tool for these engines, but in a context that is beyond the scope of this project; i.e., more sophisticated signal processing is required.

5.7.3 ALCO 16V 251B (No. 2 Engine, Port Side, Counter-Clockwise/Standard Rotation)

5.7.3.1 Loaded Engine Data Analysis

Fueling imbalances were induced in this engine by manipulating the rack of the No. 6 cylinder (seventh in the firing order) in the same fashion as was done for the No. 1 engine. ICAV traces for this engine are also shown in Figure 5.18, and remarks in Section 5.7.2.1 (above) also apply to this engine.

The normal fuel or baseline ICAV for Engine No. 2 is decidedly different from that of Engine No. 1. The engines employ reversed firing orders to produce standard (CCW) and opposite (CW) rotation. We now know there is a strong interaction between the crankshaft torsional resonance and the eighth-order ICAV which we are attempting to use for cylinder power imbalance diagnosis, and that this interaction is evidently quite different for the two firing orders. On the other hand, changes in the individual normal (baseline) ICAV as fuel imbalance (and, hence, cylinder power imbalance) is introduced appear to be of about the same relative magnitude for both engines.

5.7.3.2 Conclusions

Conclusions are the same as for Engine No. 1.

5.7.4 Analysis of Unloaded Engine Data

Part I of Table 5.4 shows the range of engine conditions over which wide-band (5 to 500 Hz bandpass) ICAV data were recorded from the unloaded main propulsion engines. Back in the laboratory the data tapes were processed with an audio-frequency spectrum analyzer, and chart recordings were made of the ICAV frequency spectrum produced at each engine test condition. A complete set of these spectra is in Appendix D.

Some of the chart recordings in Appendix D are quite noisy. This noise was a recording artifact caused by improper functioning of the instrumentation tape recorder, which was damaged in transit to the test site. Even though the tape noise was worrisome, and recorded signals were sometimes erratic, there is no reason to suspect that any other inaccuracy exists in the recorded data since the noise was definitely determined to have been caused by mechanical vibrations of faulty electrical connections inside the recorder. This means that we can reasonably expect that whenever ICAV signal data were present on the magnetic tape, it was satisfactory data. To express this a little differently, the problem was primarily dropped or missing data rather than anything being added to the ICAV signal. Fortunately, enough extra data were recorded at each engine condition to allow selection of the (relatively) cleanest portion for analysis.

Figures 5.19 and 5.20 are tracings of harmonic data for Engine No. 1 (starboard side) and Engine No. 2 (port side), respectively. These data are from the low and high ends of the engine speed range and have been corrected for baseline and frequency drift errors introduced by the spectrum analyzer equipment. Observe that they are quite similar in appearance insofar as the high-amplitude harmonic peaks are concerned. Even though there may be significant information in the many low-amplitude harmonic peaks (which are decidedly different for the two engines), we will confine our analysis to the major harmonics present and assume that anything applicable to one engine also applies to the other.

A careful examination of the high-order harmonic spectra for the two engines under conditions of over-and under-fueling at both 500 and 700 RPM does not disclose any changes which might be considered to be of diagnostic significance. This is disappointing, but it can be explained by looking at Figure 5.21 which plots in bar graph form the amplitude and frequency location of the major ICAV harmonic components up to 500 Hz at various engine speeds. It can be seen that the two major ICAV harmonics are

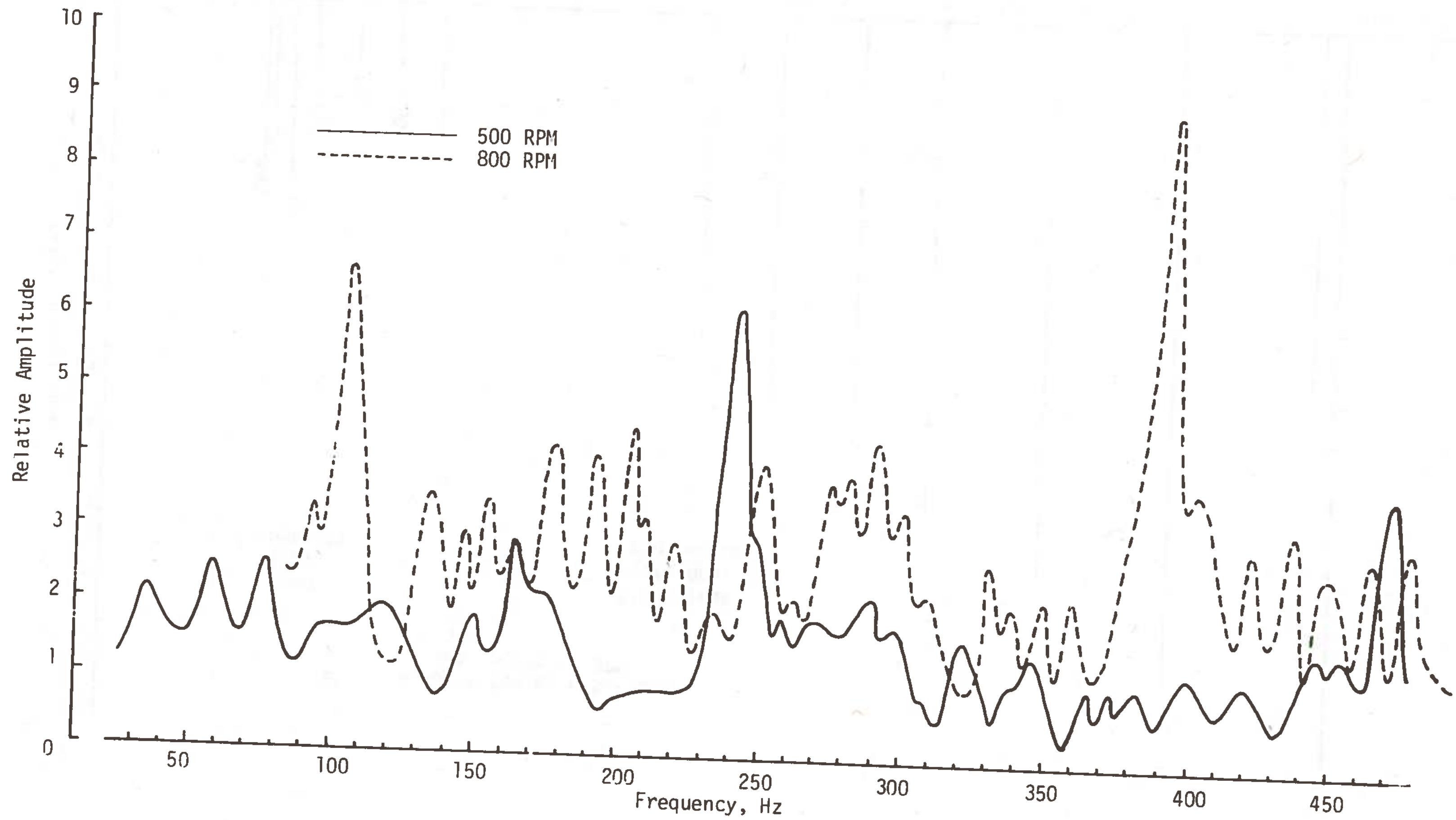


FIGURE 5.20 - HARMONIC DATA FOR USCGC COURAGEOUS, NO. 2 (PORT) ENGINE UNDER NO-LOAD OPERATION

related to each other in a ratio of about two-to-one, but not to the eighth-order driving frequency (the ICAV component of diagnostic significance). At low engine speeds there appears to be a ratio of four-to-eight to the eighth-order component, but this quickly disappears at higher engine speeds. The most significant feature displayed here is the direct proportionality of these high-order harmonics in both frequency and amplitude to engine speed. This is, of course, of no diagnostic value and in fact is the very feature of the torsional harmonic characteristics of large engine crankshafts that serves to complicate diagnosis of cylinder power imbalance by direct observation of eighth-order ICAV variations.

5.8 Caterpillar Six-Cylinder, Four-Stroke Model 3306 Engine

5.8.1 Test Procedures

A ladder tape was installed and the optical scanner with the Mk II detector used to acquire ICAV data from this engine in the laboratory at SwRI. Data were observed real-time on an oscilloscope and also recorded on magnetic tape. The only defect readily applied to this engine (which was available for only a short time and could not be modified to any extent) was underfuel in a specified cylinder. This was done by slightly loosening the fuel line connections to the desired injector and leaking off a portion of the injector pump output. This procedure allows a rather limited underfuel condition (estimated at up to 20% reduction) to be introduced without disturbing the entire injection system; however, this method did produce readily apparent ICAV changes in the engine. PKD was not measured due to the very short length of this test sequence.

5.8.2 Data Analysis

Figure 5.22 shows real-time third-order ICAV signals as photographed from the oscilloscope screen for various conditions of fueling defect, engine speed, and engine load. All signals behaved as expected, and even with this simple experimental set-up it is apparent that they could be used to diagnose individual cylinder power imbalance in this engine. The third-order ICAV signals displayed represent the direct response of the crankshaft to the individual cylinder firing events. This direct relationship (which is the diagnostically useful one) holds from idle speed (725 RPM) up to about 1200 RPM at which point extra "humps" appear in the waveform, indicating the onset of some torsional resonance.

5.8.3 Conclusions

- The data confirm that ICAV is a feasible diagnostic technique for detecting power imbalance in small- and medium-size diesel engines of similar configuration to the Caterpillar.

- The ICAV diagnostic technique used here can be applied only to engines that operate at firing frequencies far below prominent crankshaft torsional frequencies unless more sophisticated data acquisition and processing methods are developed.

5.9 Cummins 12-Cylinder, Four-Stroke Model VTA 1710

5.9.1 Test Procedures

The test procedures followed on this engine were the same as described for the Caterpillar engine in Section 5.8, above. PKD was not measured.

5.9.2 Data Analysis

ICAV signals from the Cummins engine were inconclusive and are therefore not reproduced here. Six rather than twelve angular acceleration peaks were obtained on all ICAV signal records. No filtering or equipment adjustments could be found that produced an ICAV signal that even remotely resembled a normal waveform for a 12-cylinder engine. Time was not available for a thorough examination of all possible causes; therefore, this effort must be deferred to some future time when a test engine of this type is available for a long enough period so that a careful analysis of engine geometry, firing order, and so forth can be made to discover the cause for this anomalous behavior.

5.9.3 Conclusions

V12 engines of the Cummins type must be examined for ICAV indications as a separate entity. Satisfactory ICAV signals have been obtained in the past from V6 and V8 engines of two-stroke (Detroit Diesel) type, but evidently they are different from the four-stroke Cummins as regards ICAV changes resulting from induced power imbalances.

malfunction conditions which occur in the course of service (that is, injection system faults and so forth). We also know with certainty that these large engine ICAV changes are not of the simple nature expected from small diesel engines which have short, stiff crankshafts. It is apparent that the changes in ICAV which result from cylinder power imbalance in large diesel engines can only provide useful diagnostic information when successfully extracted from a very complex assortment of flywheel angular motions produced both by the effect we are seeking to monitor (the power input contribution of each individual cylinder firing event) and by various torsional resonances in the engine crankshaft assembly itself and, additionally, in the drive train consisting of gear box, propeller shaft, and propeller.

Any future efforts toward making ICAV a useful large diesel engine diagnostic tool should include as the first order of business the acquisition of the use of a suitable baseline engine whose mechanical condition is precisely known. With this engine we must record, analyze, and accurately define the various complex flywheel angular motions which are attributable to engine geometry alone. Lack of such a baseline engine was a primary difficulty during the course of the project just accomplished. The technique of choice for baseline ICAV analysis (and later for diagnosis in a hopefully simpler form) will proceed as follows: we monitor with our already proven means the ICAV excursions which occur during each cylinder firing sequence (two complete crankshaft rotations in the case of the four-stroke ALCO engines) and time-divide this complex analog waveform into sequential digitized samples of a number sufficient to assure that we can ultimately reconstitute analog waveforms which adequately display ICAV changes of diagnostic interest. When we sample the entire firing order of 16 cylinders and make the assumption that the waveform for each cylinder firing event will require 20 or more sample points in order to obtain a waveform definition precise enough for diagnosis, on the order of 320 to perhaps 1000 samples per firing order will be required. (The sample density needed is a function of the frequency bandwidth of the desired ICAV signal, and since this quantity is derived from the ICAV signal itself we cannot now exactly specify it.) Over a period of a few hundred crankshaft revolutions (the minimum requirement will depend on engine speed), we will accumulate time samples of the ICAV excursions produced during each complete set of cylinder firing events and store these in a logic system (i.e., a computer). The computer will average the data values for each sample slot individually, and from these averages we can put into memory storage sample values which can reconstitute an average ICAV waveform which is the mean of the entire number of complete sets of firing events recorded. This information can be read out, if desired, in the form of a CRT trace or as hard-copy on conventional chart recording equipment, and one may examine the ICAV variations for a complete firing order, averaged over many revolutions. These data are the normal engine or baseline ICAV information. We next introduce known engine defects (which can be quantified) and go through the same procedure.

After obtaining this second record and storing it in memory we now have in digital storage two conditions: a normal engine condition and a maintain constant phase relationships. We know the input combustion events' time frame, but there appears to be no simple means of determining with certainty whether the excursions of crankshaft angular velocity caused by the various torsional resonances are random in time or whether they are phase-locked to the cyclic power input applied by the cylinder firing events. We would say intuitively that the input/output events should be phase-locked, yet analysis of the ICAV hard-copy chart records which we have obtained during the course of the test work discloses what appears to be a significant amount of random phase change between the various waveform components. Every torsional order group is clearly not precisely the same as every other in the hard-copy chart record. If we observe the same ICAV traces in real-time on a monitor oscilloscope during engine operation, the waveforms appear remarkably steady to the eye; that is, it has very little apparent "jitter." The significance of this observation is that so long as the real-time waveforms stand still (with scope trace synchronization being applied at the same point in the firing order for each trace) the phase relationships of the ICAV components are fixed. The two presentations (hard-copy chart and scope trace) are, therefore, not in agreement. The eye has a remarkable ability to average repetitive motions such as traces across a scope face, and this effect leads us to ignore random excursions away from the average values observed in real time. We must conclude that real-time observations of ICAV should generally be considered suspect until verified by hard-copy transcriptions or other processed read-out that eliminates this effect.

We must determine with precision, as a first order of business in any future effort, exactly what constitutes normal flywheel angular motions of a test engine in good condition and the phase relationships of the ICAV components. If phase coherence among the crankshaft inputs and outputs proves to be acceptably good (and it turns out that we have been deceived in some way by our previous method of processing the chart traces), then ICAV data processing might be greatly simplified. Let us assume that the ICAV components do indeed stay phase-locked. We may then speculate on two somewhat simpler types of data processing equipment.

A first possibility is that it may be feasible to simply subtract, by analog means, the torsional resonance component of the ICAV waveform attributable to the crankshaft alone. (This is quite different from analog subtraction of the overall ICAV waveforms.) If this can be done, the ICAV signal remaining after such subtraction might be adequate for diagnostic purposes. We know that the principal cause of distortion in the ICAV trace of these large engines (as opposed to the smaller, short-crankshaft engines) is attributable to the first torsional resonance of the crankshaft assembly. To continue this line of reasoning: if such a method proves practical, then we may say that the possibility still exists (albeit a small one) for building a cheap and simple ICAV diagnostic system that is primarily analog in nature and does not involve digital memory and microprocessor functions. The question here is whether or not ICAV signals derived by these means can be made adequate for diagnostic purposes. These possibilities can be easily examined as part of any continuing effort at

APPENDIX A

ICAV System Mark I Schematic Diagram

APPENDIX B

ICAV System Mark II Schematic Diagram

APPENDIX C
ALCO Engine Firing Orders (Standard and Reverse Rotation)

APPENDIX D

Wide-Band ICAV Frequency Spectra from Tests Onboard USCGC COURAGEOUS

This sheet replaces the 22 graphs of Appendix D. These graphs are chart recordings of not reproducible quality. However, copies will be made available to those interested recipients who request them from the Southwest Research Institute.

APPENDIX E

Report of New Technology

New technology has been developed under the scope of this contract, i.e., the system to detect Instantaneous Crankshaft Angular Velocity (ICAV) diagnostic information. Paragraphs 4.5.1 and 4.5.2 of this report present this system in some detail. A patent has been applied for, and is pending, on this new technology.

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