ELEMENTS OF DETECTION THEORY APPLIED TO NDE

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OUTLINE

- o **DEFINING "DETECTION"**
  - Practical aspects of how we think about detection
  - Differences between detection for specific NDE techniques
  - Effects of automation on detection
  - Effects of imaging on detection

- o **DETECTION IN A SIGNAL-TO-NOISE CONTEXT**
  - A basis for considering detection for all NDE processes?
  - Selected topics in Detection Theory
  - Applying Detection Theory to NDE

DEFINING "DETECTION"

- o **NDE "DETECTION" IS RARELY DISCUSSED EXPLICITLY**
  - **We probably understand it - but we don't define it**

- o **DICTIONARY DEFINITIONS** (Webster's New World Dictionary)
  - **Detect: - to catch or discover, as in a misdeed**
    - to discover or manage to perceive
    (something hidden or not easily noticed)
  - **Detection: - a finding out (said especially of what tends to elude notice)**

- o **A RADAR DEFINITION** (D.K.Barton, Radar System Analysis)
  - **Target Detection: the process by which the presence of a sought-after object, or target, is sensed in the presence of competing indications which arise from background radiation, undesired echoes, or noise generated in the receiver**

DEFINING "DETECTION"

- o **WE NEED TO DEFINE "DETECTION" BEFORE WE MEASURE "POD"**
  - **Standard NDE handbooks offer little help**
  - **The Radar definition is close to what we need**

- o **LET'S REVIEW SOME NDE TECHNIQUES**
  - **Clarify our implicit definition of detection**
  - **Assess whether the Radar definition is suitable for NDE use**

INSPECT, TEST, OR EVALUATE?

- o **DISTINGUISH BETWEEN NDT, NDI, AND NDE?**
  - **NDT, NDI, and NDE are often used interchangeably**
  - **Nondestructive Evaluation can be used as a more comprehensive term**
    - **NDE comprises all NDT and NDI activities**
    - **NDE comprises detection, location, and characterization**

- o **DETECTION AND CHARACTERIZATION ARE DISTINCT PROCESSES**
  - **In what follows, POD will refer to detection only**
  - **Caution: this distinction is not always made**
    - **Example: "POD" is sometimes used to express a measurement of performance in detecting and classifying (e.g. sizing) defects**
    - **Better termed "Joint Probability of True Positive" (Joint P{TP}) or "Probability Of Detection and Correct Interpretation" (PODCI)**

DEFECT DETECTION OR DEFECT-FREE MATERIAL?

- **SEPARATE BUT RELATED ISSUES**
  - **High POD alone does not guarantee defect-free material**
- **DEFECTS SUCCESSFULLY DETECTED**
  - **High POD suffices for selecting NDE techniques**
  - **High POD is a necessary but insufficient condition for high product life**
- **DEFECTS ESCAPING DETECTION**
  - **High product life requires a low probability that inspected material still contains any defects (compare Avioli's definition of Reliability)**
    - **Requires high POD <u>and</u> low probability of occurrence of defects**
    - **High POD may be less important if there is a very low probability of there being a defect in the uninspected material**

MAGNETIC PARTICLE AND PENETRANT INSPECTIONS

- o **SENSOR (the eye)**
  - **Responds to indication color contrast (dye) or brightness (fluoresecent)**
  - **Responds to indication shape and size (principally length)**
- o **DISCRIMINATOR (the brain)**
  - **Records high-contrast and/or large indications - the "signal"**
    - **Classifies these as "flaws" or "defects" (i.e. above threshold)**
  - **Ignores low-contrast and/or small indications - the "noise"**
    - **Classifies these as "irrelevant" or "background" (i.e. below threshold)**
- o **THRESHOLD (set by Specifications, Drawing Notes, etc.)**
  - **Typically defines maximum acceptable indication length**

RADIOGRAPHIC INSPECTION

- **SENSOR (the eye)**
  - Responds to film contrast and density
  - Responds to indication shape and size
- **DISCRIMINATOR (the brain)**
  - Records high-contrast and/or large indications - the "signal"
    - Classifies these as "flaws" or "defects" (i.e. above threshold)
  - Ignores low-contrast and/or small indications - the "noise"
    - Classifies these as "irrelevant" or "background" (i.e. below threshold)
- **THRESHOLD (set by Specifications, Drawing Notes, etc.)**
  - Typically defines maximum acceptable indication diameter (or length)

EDDY-CURRENT OR ULTRASONIC A-SCAN INSPECTION

- o **SENSOR (electronic instrumentation)**
  - **Responds to indication amplitude**
  - **Responds to indication depth**

- o **DISCRIMINATOR (an electronic threshold)**
  - **Records large indications - the "signal"**
    - **Classifies these as "flaws" or "defects" (i.e. above threshold)**
  - **Ignores small indications - the "noise"**
    - **Classifies these as "irrelevant" or "background" (i.e. below threshold)**

- o **THRESHOLD (set by Specifications, Drawing Notes, etc.)**
  - **Typically defines a maximum acceptable indication amplitude**
    - **Threshold may be related to indication phase (ET) or depth (UT)**

EFFECTS OF AUTOMATION

- **SENSORS**
  - The eye is replaced by electronic or electro-optical devices
    - Example: machine vision for automated penetrant systems

- **DISCRIMINATORS**
  - The brain is replaced by an automatic electronic device
    - Example: ultrasonic indications signalled by electronic alarm
  - The discrimination may be more quantitative, and computer-based
    - Example: penetrant indications may involve measured brightness and size

- **THRESHOLDING**
  - Thresholds may be defined more precisely, and may be more complex
    - Example: "detection" of an indication may be determined by the value of a function of several measured variables

EFFECTS OF IMAGING

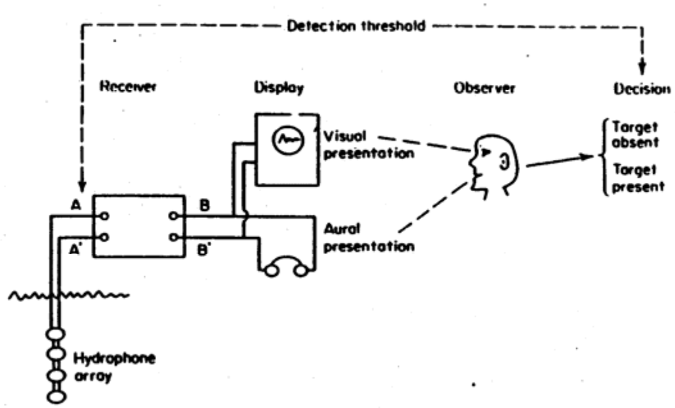
- **SPATIAL CORRELATION**
  - Imaging presents data from successive interrogations more efficiently
    - Takes advantage of spatial correlation of information
  - Facilitates use of automatic pattern-recognition and decision-making
    - Example: a computer can decide if X-ray CT wall-thickness is acceptable

- **IMAGING DOES NOT CHANGE THE BASIC DETECTION PROCESS**
  - POD is not necessarily improved by imaging
    - Example: an A-scan strip-chart contains the same data as a C-scan image
  - POD <u>may</u> be improved as a result of use a lower discrimination threshold
    - In effect, the threshold may be lowered on a local basis

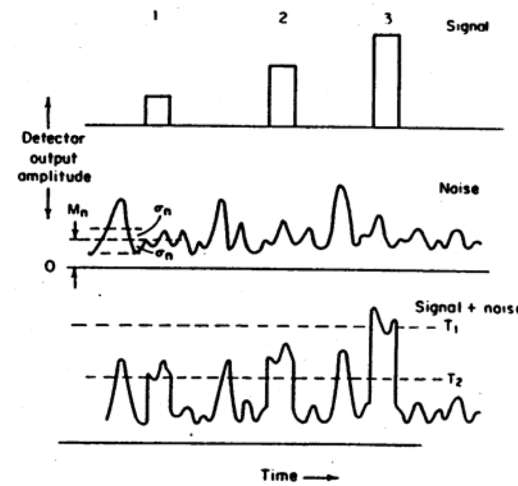
DETECTION AS A SIGNAL-TO-NOISE PROCESS

- o **NDE TECHNIQUES ARE THRESHOLDED S:N PROCESSES**
  - **Easiest to see this for "electronic" techniques (e.g. ET, UT) and for automated inspection techniques (e.g. computed tomography)**
  - **Basically true for other techniques, too (e.g. MT, PT, RT)**
- o **"THRESHOLD"**
  - **Represents a level of discrimination between "signal" and "noise"**
- o **"SIGNAL"**
  - **Represents the response from the defects - the sought-after target**
- o **"NOISE"**
  - **Competing signals from sources other than defects**

DETECTION AS A SIGNAL-TO-NOISE PROCESS



Elements of a receiving system



Signals with additive noise

- **SONAR DETECTION SYSTEM**
  - **Many similarities to ultrasonic NDE**
  - **Fundamental concepts are common to most NDE processes**

SOURCES OF NOISE

- o **NOISE FROM THE MATERIAL UNDERGOING INSPECTION**
  - **Generic examples:**
    - **Surface roughness**
    - **Edge effects**
  - **Process-specific examples:**
    - **Local changes in conductivity (MT, ET)**
    - **Indications from surface pores in castings (PT)**
    - **Grain-boundary reflections (UT)**
    - **Scattering (RT)**
- o **NOISE FROM THE INSPECTION PROCESS ITSELF**
  - **Examples:**
    - **Electronic noise (ET, UT)**
    - **Grain structure in film (RT)**

VARIATION IN THE DETECTION PROCESS

o **DEFECTS**

- Each defect has slightly different characteristics
  - Differences in size, shape, orientation, location, nature

o **MATERIAL**

- Each material sample has slightly different characteristics
  - Differences in conductivity, permeability, absorbtivity, etc.
  - Differences in shape, surface texture, etc.

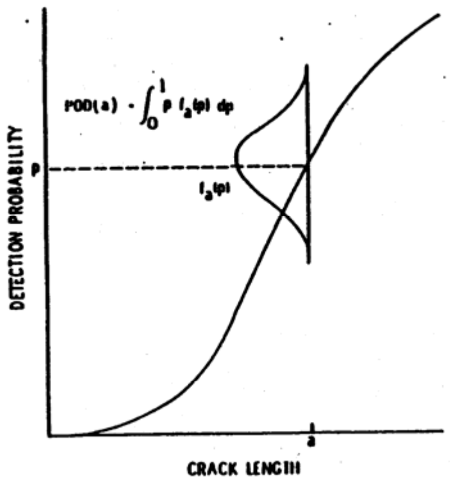
o **INSPECTION SYSTEM**

- Each inspection process has slightly different characteristics
  - Differences in penetrant concentration, etc.
  - Differences in sensitivity, linearity, frequency response, etc.
- Each inspector has slightly different capabilities

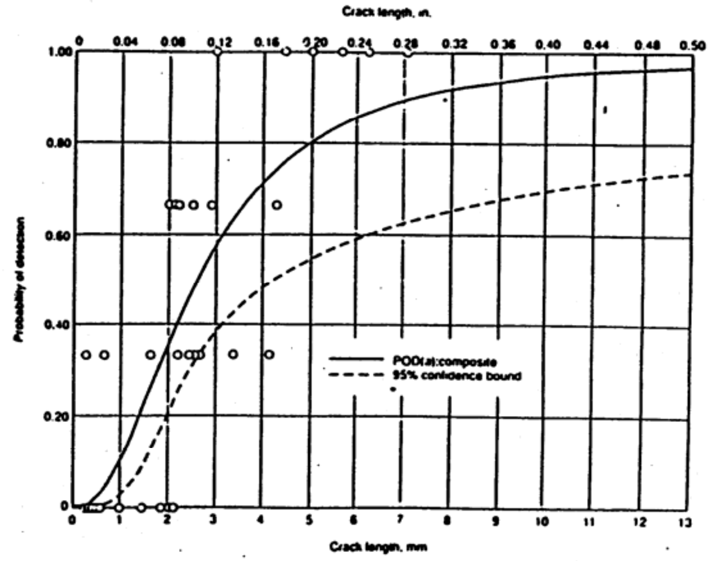
EFFECTS OF VARIATION

- o **NUMEROUS PARAMETERS CAN INFLUENCE DETECTION**
  - **Some have predictable (deterministic) effects**
  - **Many effects are not quantitatively predictable**
    - **Consequently, detection is a probabilistic phenomenon**
- o **IMPERFECTLY CONTROLLED INSPECTION PARAMETERS**
  - **Perfection is a worthy goal - but always out of reach!**
- o **SCATTER IN MEASURED DATA**
  - **Both signal and noise data incorporate the effects of variation**
    - **Measurements will yield distributions of values**

EFFECTS OF SCATTER ON POD



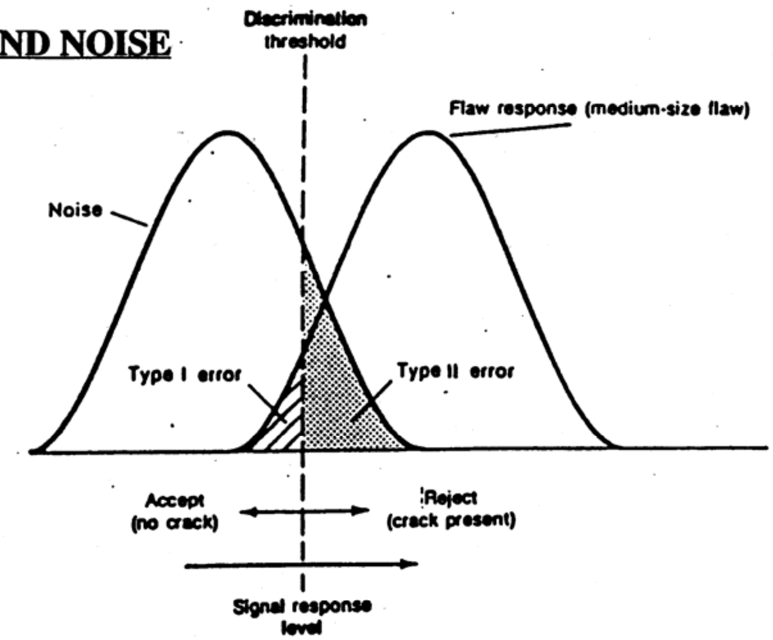
Probability density function of crack detection probabilities for cracks of a specific length



Probability of Detection data with lower one sided confidence bound representing the effects of sample size and scatter in the data

DISTRIBUTIONS OF SIGNAL AND NOISE

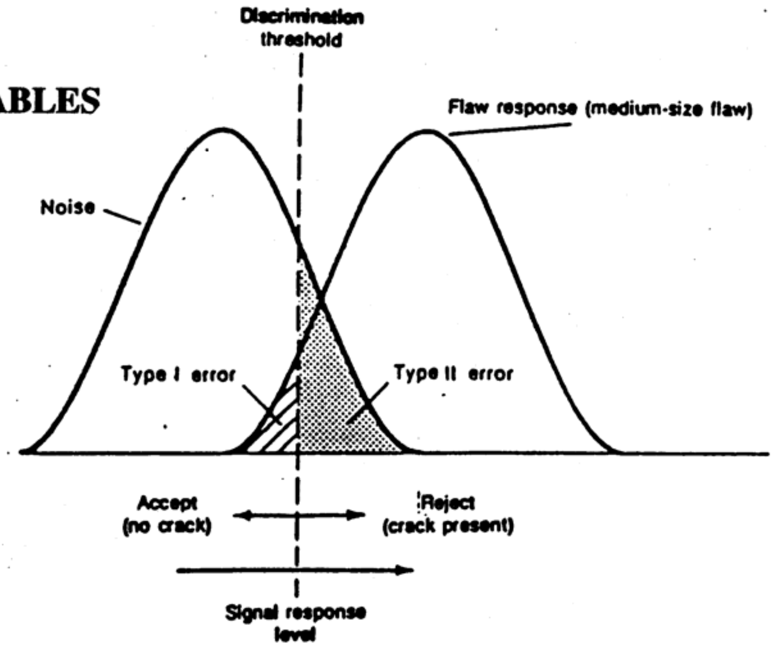
A signal-to-noise view of detection



- **AREAS ENCLOSED RELATE TO THE ALTERNATIVE OUTCOMES**
  - Detection of a defect that is present (POD)
  - Non-detection of a defect that is present (1 - POD)
  - Apparent detection of a defect that is not present (PFA)
  - Non-detection of a defect that is not present (1 - PFA)

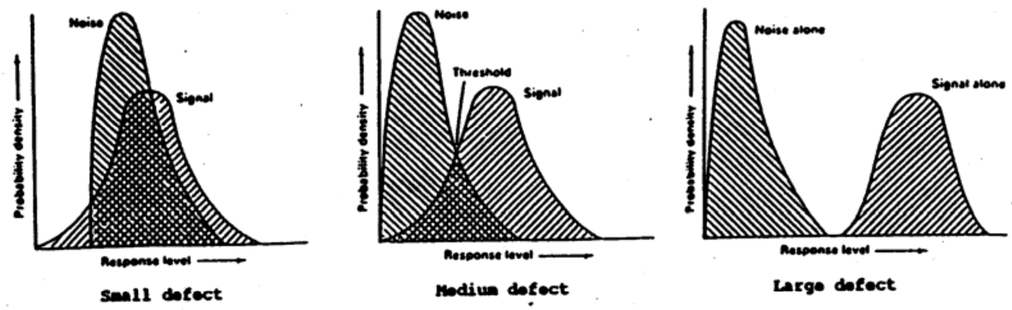
DISTRIBUTIONS OF SIGNAL AND NOISE

- o **POD AND PFA ARE CO-VARIABLES**
  - **POD is not a function of PFA**
  - **Both vary with the threshold**
    - **A lower threshold increases POD and PFA**



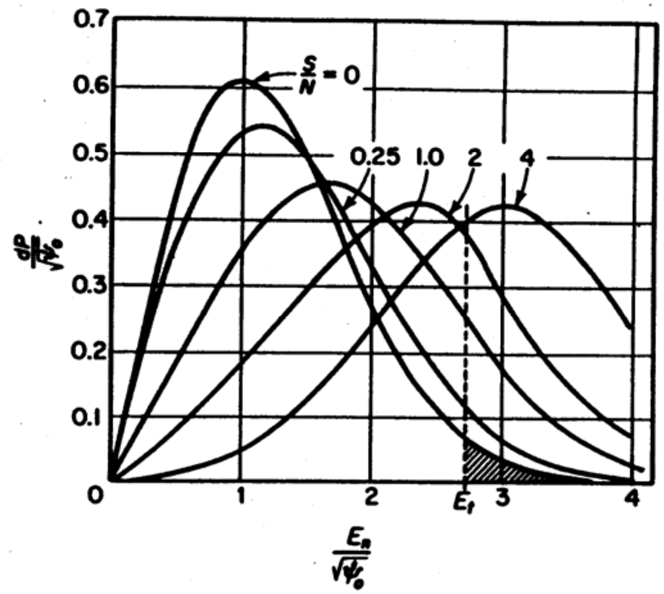
- o **CHOICE OF THRESHOLD**
  - **Difficult to keep design and manufacturing engineers happy!**
    - **Reducing Type I errors represents improved product life**
    - **Increasing Type II errors represents increased manufacturing cost**

DISTRIBUTIONS OF SIGNAL AND NOISE



- **DEPENDENCE ON DEFECT SIZE**
  - **Larger defects generally give larger signals**
  - **For a given POD, the PFA will tend to decrease with increasing defect size**
  - **For a given PFA, the POD will tend to increase with increasing defect size**
  - **For a given defect "size", POD also depends on other parameters**
    - **Shape, orientation, location, nature**

DISTRIBUTIONS OF SIGNAL AND NOISE



- **AN ALTERNATIVE WAY OF LOOKING AT SIGNAL AND NOISE**
  - **Probability distributions of envelope of signal-plus-noise**
  - **Plotted as a function of signal-to-noise ratio (S/N)**

DISTRIBUTIONS OF SIGNAL AND NOISE

- **A GATEWAY TO EXISTING SIGNAL DETECTION THEORY**
  - **Fifty years of theoretical development and practical application**
  - **NDE applications have been largely ignored**

- **STATISTICAL THEORIES OF SIGNAL DETECTION**
  - **Original applications were to radio communications and radar**
    - **Predominantly devoted to analyzing reception of pulsed signals**
  - **Based on statistical criteria for testing hypotheses and making decisions**
    - **Allow derivation of POD and PFA from noise and signal-plus-noise**
    - **Allow optimization of receiver/detector design**
    - **Provide rationale for choosing a specific detection threshold**

DETECTION THEORY

- o **RESPONSE TO A BINARY STIMULUS**
  - **Two possible states of the stimulus**
    - **Noise alone (N)**
    - **Signal plus noise (SN)**
  - **Two possible detection decisions (responses)**
    - **Noise alone present**
    - **Signal plus noise present**
  - **Four possible outcomes**
    - **N true; choose N .... true negative ..... probability (1 - PFA)**
    - **N true; choose SN .... false positive ...... probability PFA**
    - **SN true; choose SN .... true positive ...... probability POD**
    - **SN true; choose N .... false negative .... probability (1 - POD)**
- o **THRESHOLDED DETECTION**
  - **All observed values greater than the threshold are classed as SN**

DETECTION THEORY

- o **OBSERVED PROBABILITIES**
  - **Probabilities of decision outcomes are estimated from observed frequencies**
  - **These are conditional probabilities (conditional upon the stimuli)**
    - **PFA is the probability of an N response given an SN stimulus**
    - **POD is the probability of an SN response given an SN stimulus**

- o **DECISION CRITERIA**
  - **Rules to help make a choice between the two responses**
    - **Based on attaching relative importance to the four outcomes**
  - **Of many such criteria, two are of most interest**
    - **Bayes**
    - **Neyman-Pearson**

DETECTION THEORY

- o **BAYES CRITERION**

  - **Assumptions: Observer has information about the source prior to the test**
    - **Prior (or "a priori") probabilities (P_1, P_0) are known**
    - **A "cost" (C_{10}, C_{00}, C_{01}, C_{11}) can be associated with each outcome**
    - **(These may be truly known or may be educated guesses)**

  - **Goal: design the decision criterion to minimize average cost**

  - **Problem: it is often difficult to assign prior probabilities and costs**

- o **NEYMAN-PEARSON CRITERION**

  - **Assumptions: only the measured conditional probabilities are available**

  - **Goal: design a test to minimize PFA and maximize POD**

  - **Problem: these are usually conflicting objectives**

  - **Solution: set an upper limit to PFA, and maximize POD**

DETECTION THEORY

- **LIKELIHOOD RATIO TEST**
  - Bayes and Neyman-Pearson criteria both lead to likelihood ratio tests
    - Likelihood Ratio = $\dfrac{\text{Probability of choosing SN if SN is true}}{\text{Probability of choosing N if N is true}}$
  - The decision depends on whether the likelihood ratio exceeds a threshold
  - The threshold used depends on the test
    - Bayes test: threshold involves the prior probabilities and costs

$$E_t = [P_0(C_{10} - C_{00})]/[P_1(C_{01} - C_{11}]$$

    - Neyman-Pearson test: threshold chosen so that PFA = constrained value

- **AN OPTIMUM RECEIVER**
  - One that presents at its output the likelihood ratio for each receiver input
    - LR = $\dfrac{\text{Probability that given amplitude represents SN if SN is true}}{\text{Probability that given amplitude represents N if N is true}}$

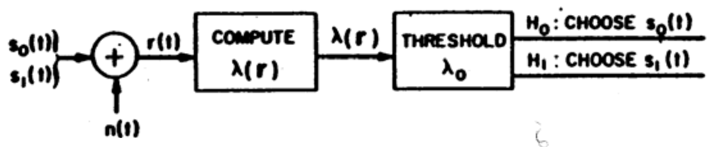
DETECTION THEORY

- o **ALTERNATIVE DECISION CRITERIA**
  - "Optimal" performance can be defined in many ways
    - Maximize True Positive while restricting False Positive
    - Maximize expected value (minimize "costs") of decision
    - Maximize percentage of correct decisions
  - Individual inspectors may apply their own criteria
    - Give priority to avoiding false alarms, or to avoiding misses, etc.

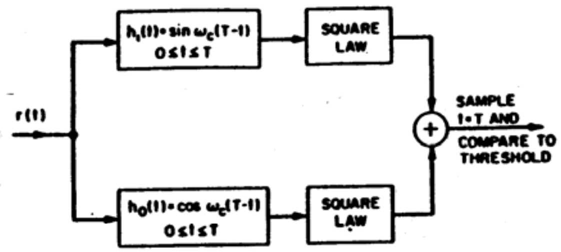
- o **HUMAN FACTORS IN THE DECISION PROCESS**
  - Inadequately trained inspectors use widely varying decision criteria
    - Human criteria tend to change with experience and/or training
      - e.g. both POD and PFA tend to decrease with time if SN is small

- o **AUTOMATED INSPECTION**
  - Decision criteria may vary, but are applied consistently

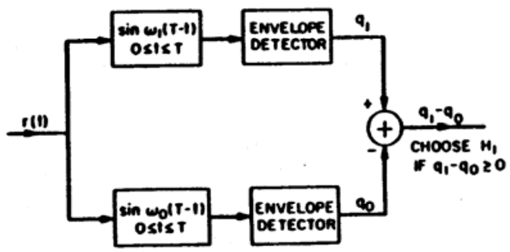
DETECTION THEORY



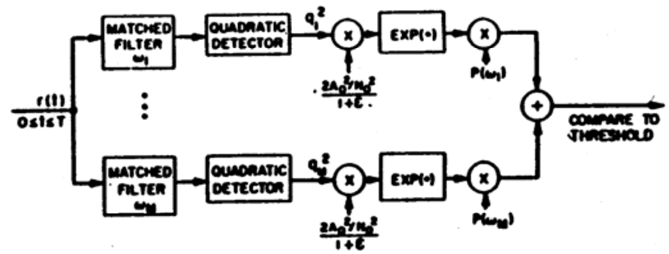
Binary communication signals



Signals of random phase



Signals of random amplitude and phase



Rayleigh fading signals of unknown frequency

- o **EXAMPLES OF OPTIMUM RECEIVERS**
  - **Signals with known or random parameters**
  - **Signals corrupted by additive white Gaussian noise**

DETECTION THEORY

- o **MEASUREMENT OF CONDITIONAL PROBABILITIES**
  - **Produce the stimulus and measure the response**
  - **Base estimates of probabilities of outcomes on observed frequencies**
- o **COMMUNICATIONS, RADAR, SONAR: relatively easy to accomplish**
  - **Switch on the signal source(s), or tell the pilot where to fly**
- o **NONDESTRUCTIVE EVALUATION: much more of a challenge**
  - **Stimuli are much more varied**
  - **True stimuli are natural, not manufactured**
  - **A "referee" technique is needed to identify the SN stimulus**
    - **For surface defects this might be optical microscopy**
    - **For subsurface defects no such technique exists**

DETECTION THEORY

- o USE OF NATURAL DEFECTS
  - Most desirable way of sampling the real defect population
    - May be difficult to obtain a truly representative sample
    - Good material quality means that defects are rare
  - Adequate characterization may present difficulties
    - Destructive examination is costly - and destroys the sample!

- o USE OF ARTIFICIAL DEFECTS
  - Allows control of at least some of the defect characteristics
    - Size, shape, orientation, location, nature
  - Difficult to truly represent the real defect population
    - What we measure is the POD for the artificial defect type
    - Still need to validate these measurements against natural defects

DETECTION THEORY

- o **SELECTION OF MEASUREMENT CONDITIONS**
  - **Goal of measurement must be clearly defined**
    - **Determines the inspection parameters**
  - **Measure "Capability"**
    - **One inspection of a sample of defects of "identical" or differing size**
  - **Measure "Repeatability"**
    - **Multiple measurements of a defect sample by the same inspector/system**
  - **Measure "Reproducibility"**
    - **Multiple measurements of a defect sample using "identical" conditions**
  - **Measure "Variability"**
    - **Multiple measurements of a defect sample by different inspectors/systems**
  - **Measure "Reliability"**
    - **Multiple measurements of a defect sample using all these factors**

DETECTION THEORY

- o **MEASUREMENT OF POD ALONE**
  - **Acceptable: POD is not dependent on PFA**
    - **Knowledge of POD is adequate for determining capability and reliability**
    - **Knowledge of POD is adequate for predicting product life**

- o **MEASUREMENT OF POD AND PFA**
  - **Recommended: a more complete description of the detection process**
    - **Knowledge of PFA helps select an optimum threshold**
    - **Knowledge of PFA helps identify manufacturing costs**

- o **MEASUREMENT OF ALL FOUR OUTCOMES**
  - **Not recommended: POD and PFA fully describe the detection process**
    - **Probability of a false negative (a miss) is the complement of POD**
    - **Probability of a true negative is the complement of PFA**

SOURCES USED

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