LLOYD'S REGISTER'S TECHNICAL INVESTIGATION DEPARTMENT
SOME INTERESTING INVESTIGATIONS AND EXPERIENCE GAINED FROM 50 YEARS OF OPERATION

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ABSTRACT

The article marks the fiftieth anniversary of Lloyd's Register's Technical Investigation Department and considers some of the experience gained during troubleshooting and problem solving activities since the Department was formed. Following a brief resumé of the origins of the Department and its work, attention is turned to the various full scale experimental and computational techniques that have been developed. The most common forms of failure encountered today are identified and discussed, as are the more usual types of shipboard vibration excitation. Several examples of interesting or novel investigations in the marine, land-based and offshore industries which embrace specific engineering lessons are outlined. The article finally moves to a discussion on the Department's work in the condition monitoring of marine machinery and land and offshore structures before concluding with some comments based on the more general experience gained during the course of the Department's activities.

Introduction

'Those who do not remember the past are condemned to repeat it'.

So wrote the Spanish born philosopher George SANTAYANA in the early years of this century.[1] Although this caution was expressed in the context of general philosophical and political argument, it is nevertheless true for engineering design and operation. This is because engineering is not a precise science; rather it is a combination of scientific method and engineering experience combined with manufacturing and operational practice and capability. This article, drawing as it does on the experience gained during the course of engineering investigation, seeks to contribute to the body of knowledge on the causes of engineering failure and unexpected performance together with the methods by which this can be investigated.

The Technical Investigation Department (TID) of Lloyd's Register (LR), since its formation fifty years ago, has been invited to investigate some of the more intractable engineering problems posed by the marine industry. It has done this by a combination of trial measurement, theoretical analysis and engineering judgement based on the Department's accumulated experience. This experience has embraced a full range of failure and mal-performance based engineering problems from the marine, land-based and offshore industries. To address these problems TID comprises a multi-disciplinary group of engineers and scientists which includes:

- Mechanical, marine, civil and structural engineers
- Naval architects
- Physicists
- Electrical and electronic engineers
- Mathematicians
- Computer scientists
- Statisticians.

The talents of this relatively unique group of highly qualified engineers and scientists are combined to provide a high quality, rapid response, technical consultancy and advisory service to the marine industry, the other industries that LR serves and to LR itself. These activities are supported by instrumentation and material investigation laboratories. The Department also conducts medium and long term marine engineering research and development to equip LR, in keeping with its divisional strategies, with the necessary capabilities to meet future requirements based on a continuing review of technological development. Clearly, by the nature of the Department's primary work, many of the research initiatives derive from the failure scenarios presented to TID.

Many engineering investigation activities involve an iteration which commences with a hypothesis about the failure mechanism or the underlying cause of an unexpected performance. From the initial working hypothesis, either a suitable instrumentation fit and trials programme is prepared or, alternatively, a theoretical model is derived to test the validity of the hypothesis. In the former case, following the full scale trials stage of the investigation, an analytical or numerical model may be formulated in order, first to obtain correlation with the quantitative trials data set and then, secondly to extend this domain so as to formulate proposals for appropriate remedial action. In the latter case a similar procedure applies but without the benefit of measured data, the correlation being undertaken by comparing the predictions with the observed qualitative behaviour and other standard test cases. In these cases significant demands are placed on the selected analytical or numerical procedures which, in turn, require that the chosen methods are well correlated and that their predictions can be generally supported by less detailed methods or heuristic insights into the appropriate behaviour. For both situations the accumulated experience of past failures and the factors involved in their manifestation are an essential ingredient. Consequently, to satisfactorily execute an investigation a unique blend of measurement and theoretical analysis combined with a sound historical knowledge of failure situations are essential for each case.

Origins and work of the Department

Lloyd's Register's Technical Investigation Department was formed in 1947 under the then Chief Engineer Surveyor, Dr S.F. Dorey. His primary purpose in forming the Department was:

> 'To give LR a capability to explore marine failures and to research technical problems with a view to improving the Rules.'

This vision has remained the guiding principle for the Department to the present day. However, when dwelling on the work of TID it should not be concluded that LR commenced its interest in failure mechanisms and Rule development at the time of TID's formation. Clearly, prior to this time LR had undertaken significant amounts of research and development as witnessed by both the stage of development of the 'Rules' at the time TID was inaugurated and the various references in LR's Annals to Principal Surveyors for Research.

At the time of its formation much of the Department's early work centred on torsional vibration problems, hull vibration and material fatigue. In the case of hull vibration, an extensive series of studies were undertaken in 1947 on a wartime ship in the River Fal in Cornwall using a purpose built exciter made in the Department. In contrast, the work on metal fatigue took place in an old earth floored laboratory, once used by STEPHENSON, in the Stavely Iron Works. Recognizing the importance of specimen size on the results of fatigue tests, in order to maximize specimen size the equipment used for this work was designed by members of the Department to function on an electrically induced resonance principle. Although designed by them and their colleagues, this equipment was not entirely liked by the members of the Department assigned to undertake the experiments as during the lengthy trials the resonance properties of the machines varied in sympathy with the electricity grid loads and needed constant fine adjustment by the Surveyors around the clock.

The earliest consultancy report that survives in the Departmental archives is dated the 18 September 1948 and relates to a torsional vibration investigation on the main machinery of the M.V. *Turoy*, conducted during trials on the River Humber. Since that time a complete set of TID's reports is maintained in the Department's library. Apart from the longer term research work in ship and machinery vibration which formed an underlying theme of the Department's work, consultancy investigations rapidly settled down into two relatively distinct types. These were problems with ship's machinery or structure which persisted while the ship was operating at sea and which, therefore, had to be investigated at sea and, secondly, major failures which occurred at sea and incapacitated the ship, consequently causing serious delay. This is a distinction which continues to the present time.

From the beginning TID needed to provide a rapid response service to any part of the world and this was made possible by the growing international airline network. However, even by 1951 the novelty of TID surveyors providing this kind of service still warranted mention in the Annual Report:

> "Surveyors of the engineering research department have flown many thousands of miles in the past year to investigate urgent problems on behalf of shipowners and ship and engine builders."

Today the Department's ability and reputation for responding rapidly to calls for assistance are rightly taken for granted by clients and LR alike. Since the Department's formation it has undertaken 4,775 investigations up to the end of 1996 and the growth of these with time is seen in (FIG. 1). An increasing demand for the services on offer can be seen with areas of significant activity in the late 1950's and early 1970's. The fall off in the last year has been due to the separation of LR's environmental activities into a specialized department which had previously been grown to a mature state within TID through LR's Marine Exhaust Emissions Programme[2] and work on Ro/Ro vehicle deck emissions and habitability. Indeed, throughout the life of TID there have been several examples of particular activities forming and being developed to a suitable stage where specific services could be offered to industry.

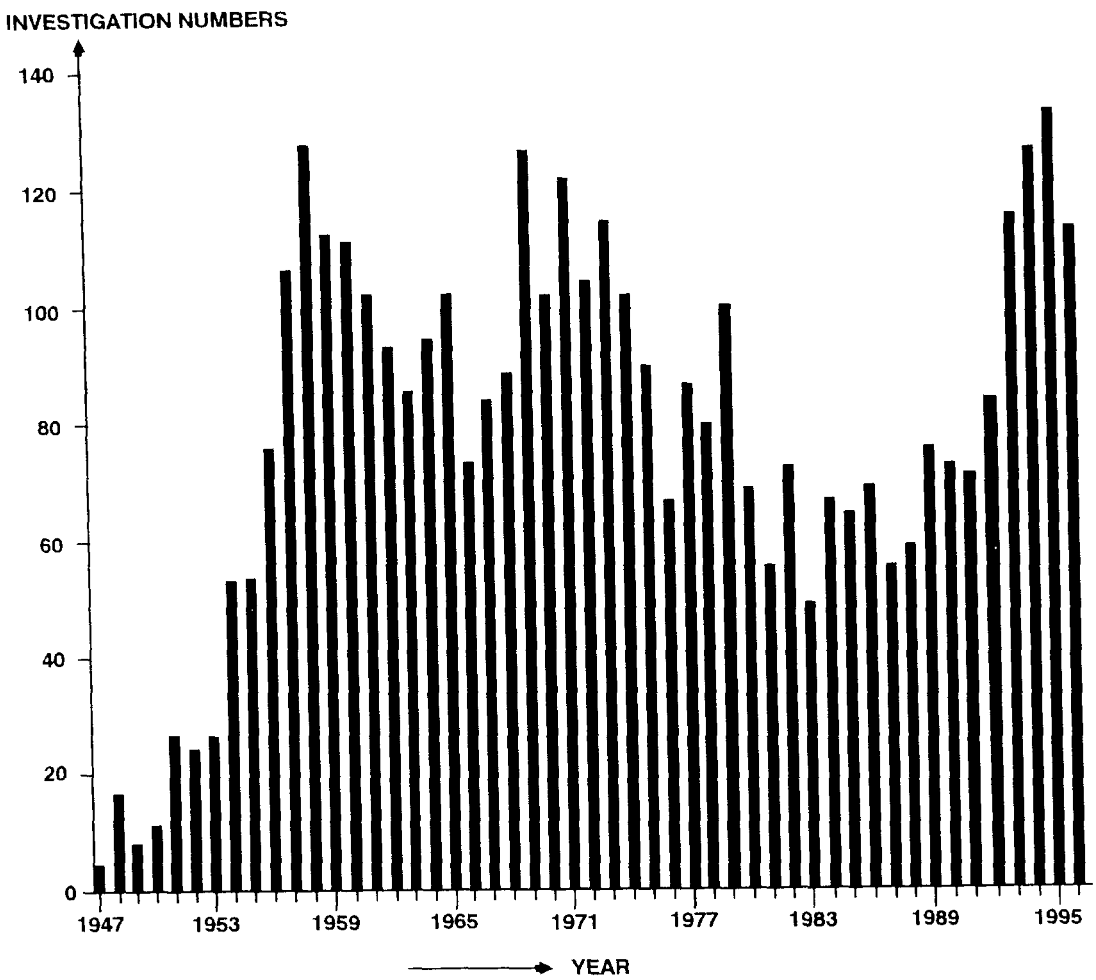


FIG. 1—DISTRIBUTION OF INVESTIGATIONS BY YEAR

Analysis of the Department's database, Table 1, shows the distribution of investigation types that have been undertaken in each of the marine, land based and offshore sectors. The subdivision of the marine categories in the Table is more extensive because this area forms the major part of the Department's work. As such, the miscellaneous category in the marine grouping is significantly smaller than the other two where, for example, a wide range of investigation work is undertaken that does not conveniently fit into the standard categories.

TABLE 1—*Primary Classification of Investigations 1947—1996*

Marine	%	**Land Based Industries**	%	**Offshore**	%
Hull/Mach. Vibration	25.8	Petro-Chem/ Indust	21.7	Platforms	58.3
Shafting	24.1	Power Stations	20.3	Miscellaneous	33.3
Diesel Engines	14.1	Miscellaneous	18.5	Pipelines	8.4
Gearing	9.1	Buildings	17.0		
Power Absorption	5.8	Nuclear	14.5		
Noise	2.7	Docks and Harbours	4.7		
Turbines	2.5	Bridges	3.3		
Electrical	2.4				
Propellers	2.1				
Auxiliary Machinery	2.0				
Condition Monitoring	1.9				
Boilers	1.6				
Couplings/Clutches	1.5				
Ship Structural Failure	1.2				
Rudders	1.1				
Environment	0.9				
Miscellaneous	0.8				
Pipelines	0.4				

When considering the data presented in Table 1, clearly these assignments have not been equally distributed over the years. Indeed, in TID's experience, it is a general characteristic that investigations tend to be grouped into subject areas for discrete periods of time. (FIGS. 2, 3 and 4) show typical examples of the variable trends with time for hull and machinery vibration, shafting, and diesel engine investigations; these being the three largest categories shown in Table 1.

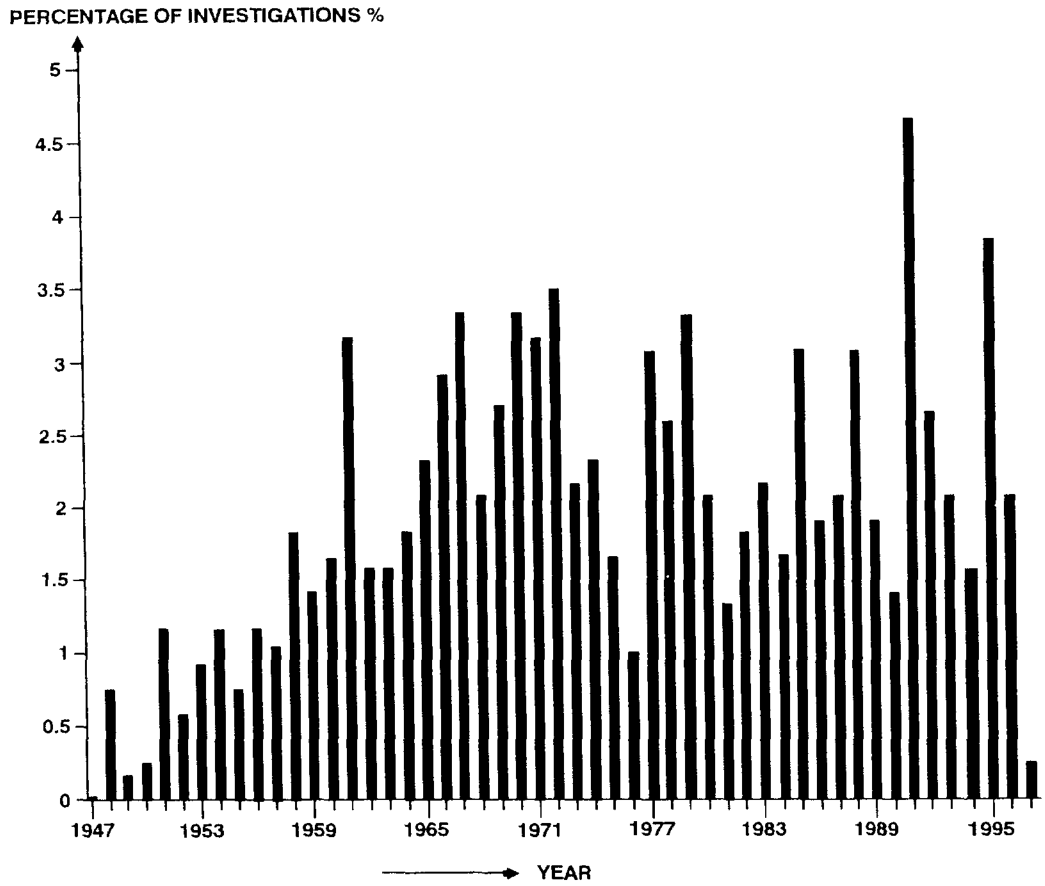


FIG. 2—DISTRIBUTION OF HULL AND MACHINERY VIBRATION INVESTIGATIONS

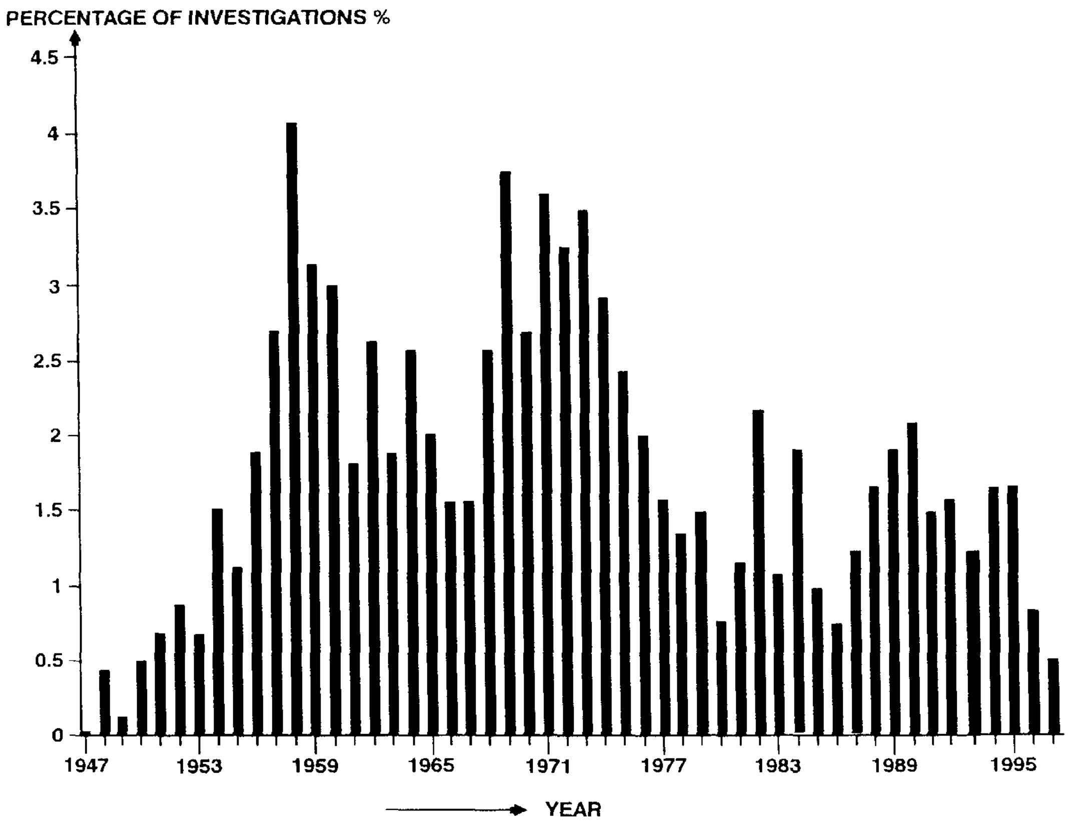


FIG. 3—DISTRIBUTION OF SHAFTING INVESTIGATIONS

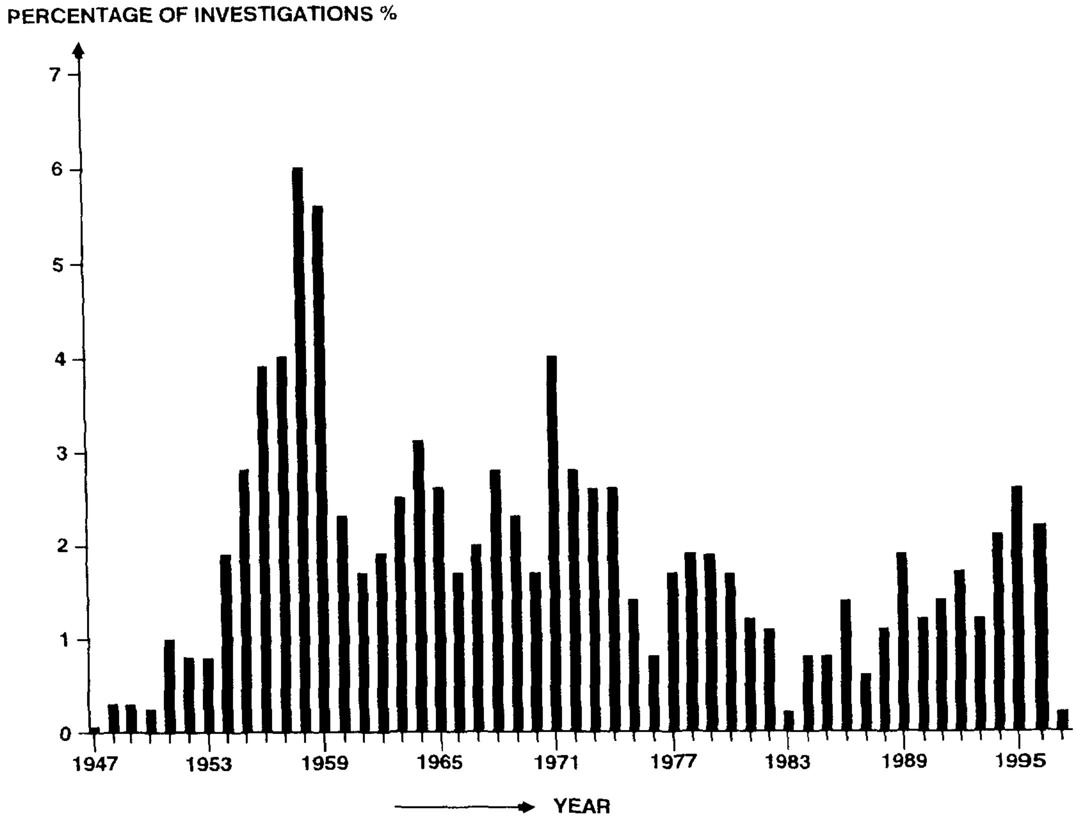
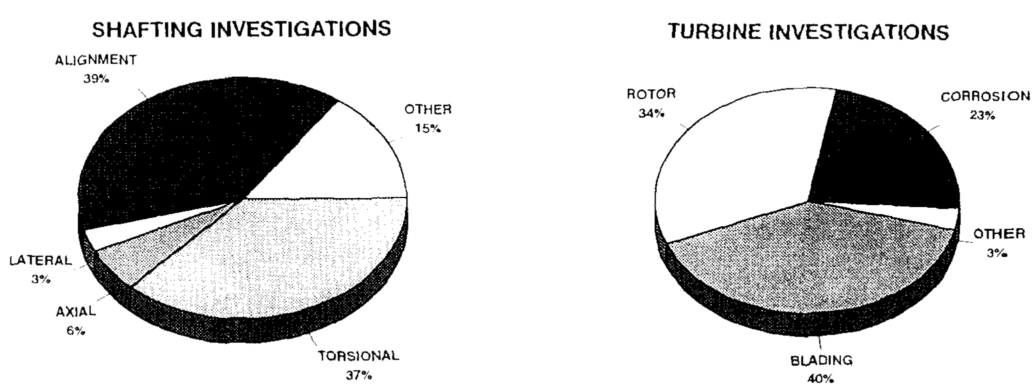


FIG. 4—DISTRIBUTION OF DIESEL INVESTIGATIONS

Within the various general categories there are some cases where subdivisions of investigation activity are of interest. These are shown in (FIG. 5) for the general categories of:

- Shafting
- Turbines
- Diesel engines
- Boilers
- Propulsors
- Electrical investigations.



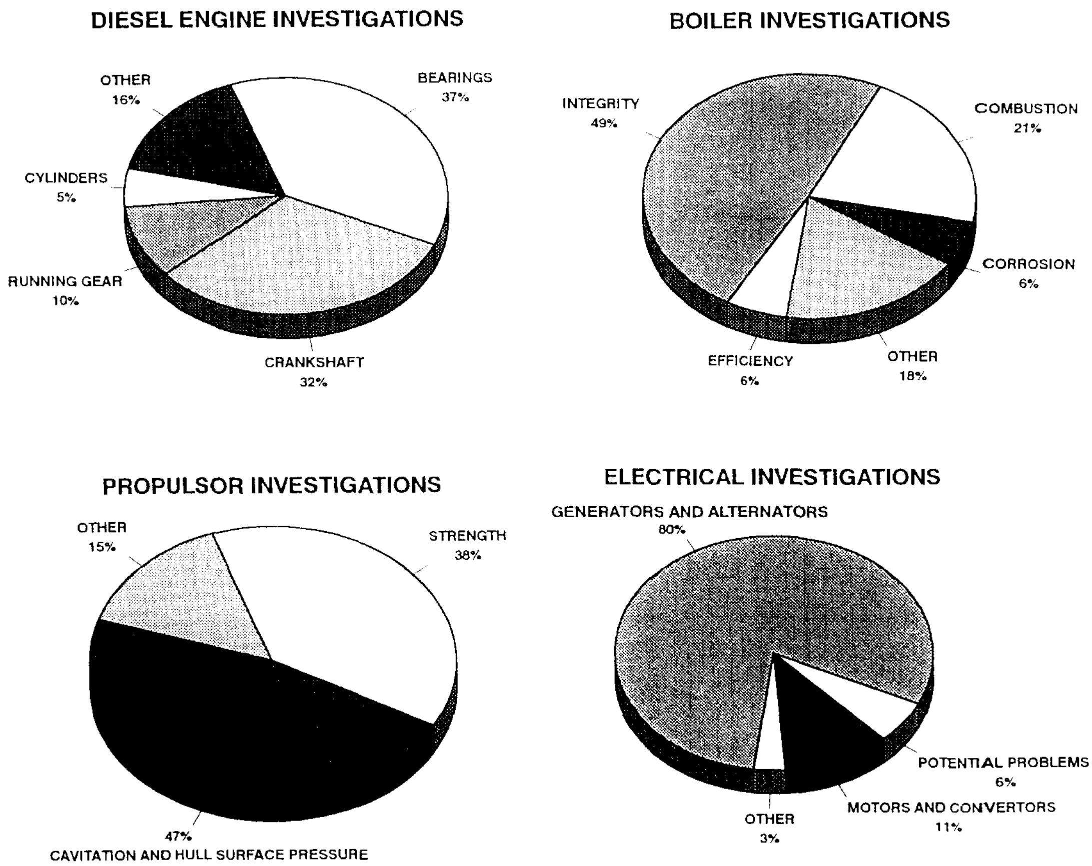


FIG. 5—SUBGROUPING OF SOME INVESTIGATION CATEGORIES

The ability to take engineering measurements in a wide range of environmental and in-service conditions, when coupled to an analysis and interpretation of the results, has enabled the Department to undertake a wide range of technical verification tests. LR's reputation for independence, integrity and impartiality provides an important cornerstone for these services.

Apart from the routine work associated with ships' acceptance trials; power measurements, noise and vibration surveys and bollard pull certification for tugs, there have been many unusual applications for TID's expertise, especially in measuring strain, displacement and acceleration.

The manufacturers of aviation flight simulators have adapted their product to perform fun rides in modern theme parks. These motion machines are subjected to stringent design safety assessments and subsequent operating licence regulation by the relevant National authorities. Cyclic loading of the fabricated lattice structures is a difficult design problem and fatigue cracks have occurred in some installations. Full scale stress measurements have become an integral part of the design verification procedures. Strain gauge positions are selected after studying the results of finite element calculations, and typically about 50 three-element rosettes are fitted. The strain measurements together with the hydraulic actuator loads and displacements are recorded by data-loggers, not only for the normal ride sequence, but also under simulated failure conditions. TID analyse the data to give the principal stress fluctuations which are then used in conjunction with welded joint fatigue life design limits to estimate the endurance of the structure.

Similar strain gauge measuring techniques are used in pressure vessel hydraulic tests and also for occasional pneumatic tests. For this work it is normal practice to fit the strain gauges on each side of the vessel's shell to differentiate between membrane and bending stresses. Ultrasonic methods are used to align the external and internal gauges on the shell or re-inforcing plates. Techniques have also been developed to waterproof the internal gauges and their electrical connections for pressures up to 200 bar.

One particularly interesting use of strain monitoring is during the mechanical stress relief of large containment structures. This procedure is usually applied when thermal stress relief is impractical due to the size of the pressure vessel. The principle of mechanical stress relief is to subject the vessel to hydraulic pressure cycles such that it attains a stress-stable condition with fully elastic behaviour up to the 'standard' test pressure. Structural response in the vicinity of stress concentrations is measured by strain gauges and acceptance is based on a demonstration of elastic characteristics at the gauge positions during two consecutive cycles up to the 'standard' pressure. ASME VIII Division 1 specifies the appropriate requirements for the test procedures.

Acceleration measurements were central to the testing of a novel capsule which was intended as an emergency escape from offshore platforms. The capsule was designed to operate as a free vertical fall unit with adjustable ballast so that on impact with the sea it would have a slightly negative buoyancy. A small propulsion motor could then propel it as a submerged craft beneath any fire surrounding platform, before the ballast was discharged. It was hoped that drops exceeding 25 metres might be feasible if suitable suspension arrangements for the occupants could be devised. When the capsule was released from a barge mounted crane the best seating arrangement, according to the dummy occupants on board, was supported by a rigid suspension. The various alternative arrangements incorporating springs, hydraulic and gas dampers gave higher accelerations, which in some cases were sufficient to break the safety harnesses during the recoil. It is suspected that the project test programme may still be waiting for its first human volunteers!

Not all investigations fall into the traditional mould of marine and industrial problems. Some, while being serious in their own right, are memorable for the circumstances in which they were carried out. One such example from the 1960's concerned an upper floor dance hall above some shops with large plate glass windows. Dances were held on Saturday nights together with a non-stop lunch time session. Problems arose when shoppers were on occasions startled to see the plate glass windows bulging rhythmically and tins bouncing on the shelves in harmony. After several evenings spent measuring vibration on and around the dance floor, with notebooks bearing such unusual entries as *Quickstep—2.5 cycles per second*, TID surveyors established that the dancers, particularly in their interpretation of the latest hit *March of the Mods*, were exciting the resonant frequency of the main girders supporting the floor. The problem was solved by placing pillars at strategic points under the girders. This is one example where building vibration has provided an interesting investigation: other examples have been associated with the:

- Piling action for locks on a river and its effect on ancient buildings
- Condition monitoring of post tensioned concrete bridges
- Effect of passing heavy London traffic on historic buildings.

Development of measurement techniques

As highlighted earlier, the diagnosis of machinery failures or mal-performance requires many skills in order to develop a satisfactory solution. The use of appropriate measurement capabilities is one aspect of the problem and TID uses both standard 'off-the-shelf' instrumentation and also, where necessary, develops equipment or measurement techniques to meet the needs of particular or a class of investigations. In all cases of standard or developed instrumentation, to be of value the instruments must have traceability to national standards and TID rigorously adheres to this policy.

In marine field investigations ease of instrument application is a critical parameter; both with respect to the time required to install equipment and to the level of instrumentation skills needed. To illustrate this point, strain gauges have been fitted by Departmental staff in the last twelve to eighteen months in temperatures as low as $-25°C$, in snow storms and rain or in the humidity and temperatures of the tropics. These various installations have, when complete, been required to work in nominally dry or wet conditions, interfacing with a variety of fluids, to be fitted to shafting systems which could not be stopped and be exposed to operating temperatures of several hundreds of degrees. As for time constraints, these can be exacting; recently, for example, in order to coincide with a ship's sailing schedule a system of ten shaft alignment strain gauges was fitted to the shaft, wired up, calibrated and the alignment trial undertaken in 4 hours.

The underlying philosophy relating to engineering investigations is that, if possible, measurements, or for that matter computations, made by one generic form of procedure are to be supported by those from a different generic form. Additionally, as an investigation proceeds and particularly if it is of an exploratory nature, it may be necessary to improvise or develop instrumentation in the field which can be a difficult undertaking in some of the remoter locations of the world.

The development of new instrumentation or methods can be either short or long term, depending upon whether the result is required for a particular assignment or for a generalised investigation procedure. By way of example of the short term development, the expansion of the UK Nuclear programme in the late 1950's and early 1960's led to an urgent requirement for the TID Laboratory to develop new encapsulation methods for strain gauges; the annual usage being of the order of 10,000. The majority of the technical development work is normally carried out in our laboratory, (FIG. 6), and in some cases may extend over a number of years. Examples of longer term developments have been strain gauge shaft alignment, gear tooth root strain techniques, propeller blade strain measurement, data transmission and remote trial control methods.

Shaft alignment

The self weight of the shaft, the overhung propeller and its associated operational loads, gear wheel meshing and the flexibility and loading of the ship's structure combine to make the alignment of the shaft supports, both in height and attitude, a non-trivial process. In addition to the operational loads, deflections from the nominal may also arise from:

- Structural deformation as the hull is welded,
- Thermal distortion of the structure due to the sun,
- Variations in attitude between dry docking and afloat, and
- Residual stresses which may relax once a service load has been experienced.[4]

As far back as 1951, methods by which the alignment of marine shafting could be undertaken without breaking the couplings were being developed by members of the Department. This early work resulted in an alignment indicator which was a three point support instrument comprising an Invar chassis and a strain gauged Tufnol cantilever with a hardened steel insert. The instru-

FIG. 6—TID LABORATORY—EQUIPMENT PREPARATION

ment was clamped to the shaft and measured the change of strain as the shaft was rotated using the turning gear. This measurement procedure was superseded in the early 1960's by the direct use of strain gauges bonded to the shaft. The practical interpretation of these measurements, the corresponding theoretical calculations and the results of other alignment techniques have been continuously developed to the present day.

The basis of the strain gauge method is that the bending moment at any station in the shaft can be considered as comprising two components: the moment arising from self weight with the bearings positioned in a straight line and the moment arising from the deflections from the straight line condition. To measure the actual bending moment in a shaft, (FIG. 7), strain gauge half bridges are fitted, usually at two stations per span. By using pre-encapsulated, pre-wired gauges, with fast curing resin or cyanoacrylate adhesives, reliable installations can be applied very quickly. After instrumentation the shaft is rotated through 360° using the turning gear, with strains measured at 90° intervals to obtain bending strain data for the vertical and transverse alignments. The differences in strain across the diameter are used to evaluate the shaft bending moments. The straight line bending moments are calculated from a theoretical representation of the shafting system together with the influence coefficients for the load-deflection response at each bearing. By subtracting the straight line bending moments from the measured bending moments and using the computed influence coefficient data a desired alignment to meet the operational conditions can be derived. Furthermore, from a proper treatment of the system boundary conditions, loads on inaccessible bearings in the gearbox or at the stern tube bearings can be determined. The measurement procedure is applied in either the hot or cold state and the ballast and loaded conditions. In more complex situations, the procedure can be employed dynamically by using radio telemetry systems for signal transmission.

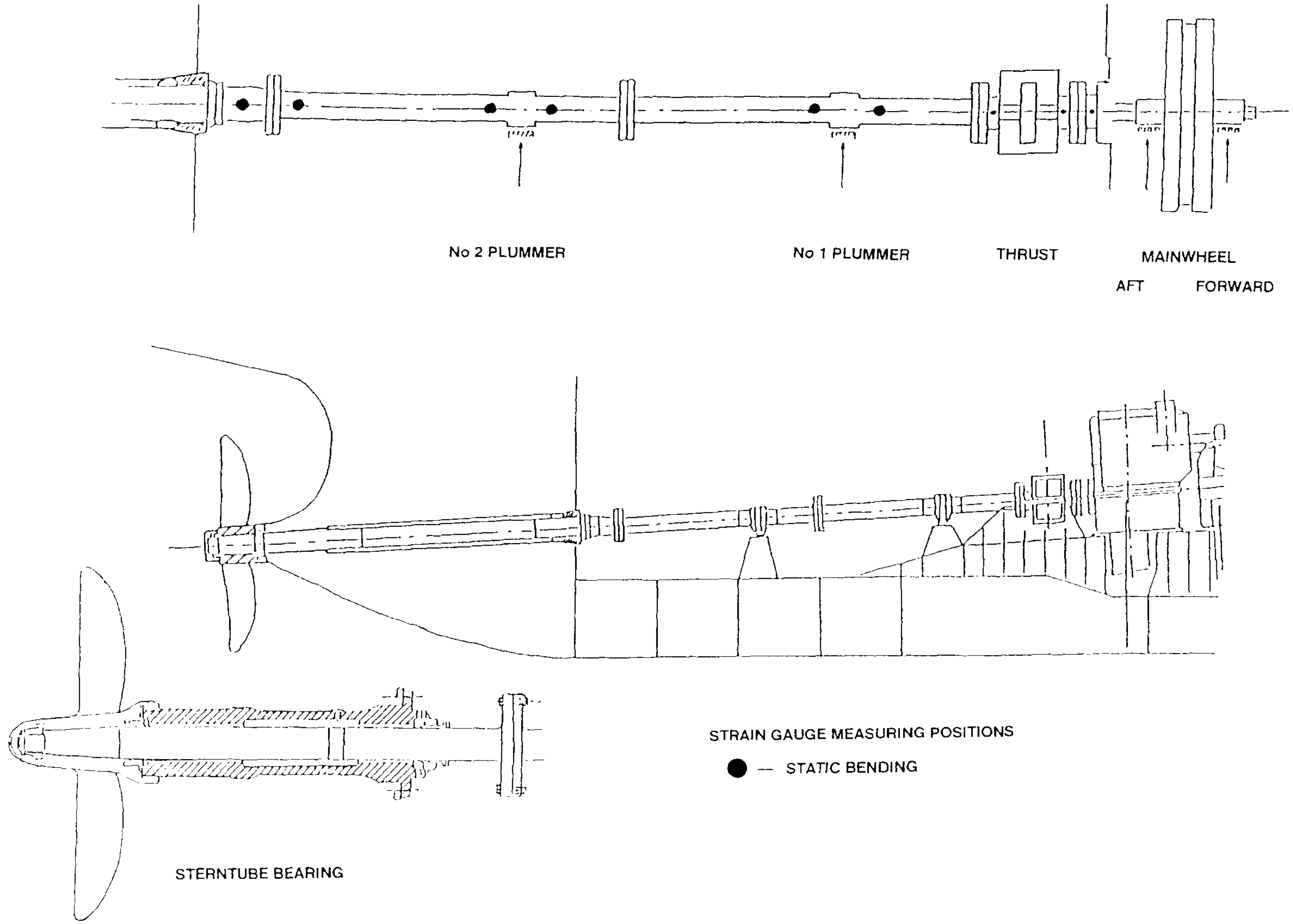


FIG. 7—TYPICAL ALIGNMENT STRAIN GAUGE CONFIGURATION

This method of alignment is particularly useful in investigation situations. However, it does have some disadvantages, as indeed do the other more commonly employed methods of jacking and measuring gaps and sags. In line with the Departmental philosophy strain gauge alignment results would, where possible, always be confirmed with a jacking trial as the two methods tend to complement each other. Some relative merits of the three methods are compared in Table 2.

TABLE 2—*Some relative merits of alignment methods*

Method	Advantages	Disadvantages
Strain Gauge Method	• Shafting is fully coupled • Journals are in their normal static attitude in relation to the bearing surfaces • Gives results for inaccessible bearings • Gives vertical and transverse alignment results • Quantifies the loads imposed by the propulsion shafting on direct drive diesel crankshafts • Easily applicable to investigate the effects of draught and machinery temperature	• Time and skill needed to fit the strain gauges • Arrangements are needed to turn the shaft • Relies on a theoretical calculation • Does not detect a bent shaft
Jacking of Bearings	• Shafting is fully coupled • Uses simple equipment • Gives information that can be used to estimate the bearing adjustments • Can detect a bent shaft	• Can be used only for accessible bearings • Is impractical for transverse bearing loads • Support conditions at adjacent bearings are affected as the shaft is raised. • Hysteresis can cause significant uncertainty in the results: either from the friction in the jack seals or between the journal and bearing surface. Can be partly counteracted by using a load cell rather than the jack hydraulic pressure. • Interpretation of the results can easily be erroneous if adjacent bearings become unloaded as the shaft is raised. • Theoretical calculations are needed to derive correction factors if the jack is not positioned close to the bearing, or the shaft span to an adjacent bearing is small.
Gaps and Sags	• The most convenient way of establishing the alignment of the machinery relative to the sterntube bearings during newbuilding • Simple measurements. • Addresses vertical and transverse alignment.	• Shafting must be uncoupled. • Temporary supports are often needed. • Coupling flanges must be in good condition—uncorroded. • Shaft alignment is sensitive to measuring tolerances and small errors.

Gear tooth strain measurement

Within a typical marine gearbox there are many mechanical and thermal interactions; for example, between the gearbox housing and hull structure, the relative attitude of the various components within the gearbox, thermal effects due to loading or lubrication systems, manufacturing deficiencies and the power transmitted. The traditional method of examining the contact markings across gear teeth is by the use of Engineers' Blue or hard lacquer. The disadvantage of these methods is in the variations of load distribution that may be encountered as the transmission torque load is increased throughout the power range or, alternatively, during transient conditions such as propeller ice contact. To overcome these types of problems the techniques and advantages of measuring the root strains in the teeth of the pinions or wheels of gear trains were further developed from the original work of PINNEKAMP.[5]

To monitor the operating strain distribution across the teeth would require many channels of strain gauge instrumentation. To address this consideration an elegant use of the Wheatstone bridge has been evolved, FIG. 8. Strain gauges are mounted in the roots of successive teeth, outside of their respective areas of contact, and connected into the bridge circuit. The signature which results as the wheel rotates takes the form shown in FIG. 8. Thus four, or even eight, strain values depicting the general tooth root stress distribution can be obtained from one channel and, if non integer tooth ratios are present, the differences between the meshing of individual teeth can be distinguished. Most importantly, the effects of load sharing, alignment and helix mis-match can be monitored throughout the speed range. The installation of strain gauges in the roots of gear teeth requires the use of miniature gauges, of about 1.0 mm gauge length, together with high levels of expertise; particularly as the work is often done with the gears in situ. The measured strains are transmitted from the rotating gear component by means of radio telemetry and (FIG. 9) shows an installation of such a system.

To interpret the large quantities of measured data satisfactorily, computer based statistical techniques are employed in order to separate the mean load distributions from the tooth to tooth variations inherent in the meshing process. In these trials the absolute strain levels are of less importance than their qualitative variation with loading and running conditions.

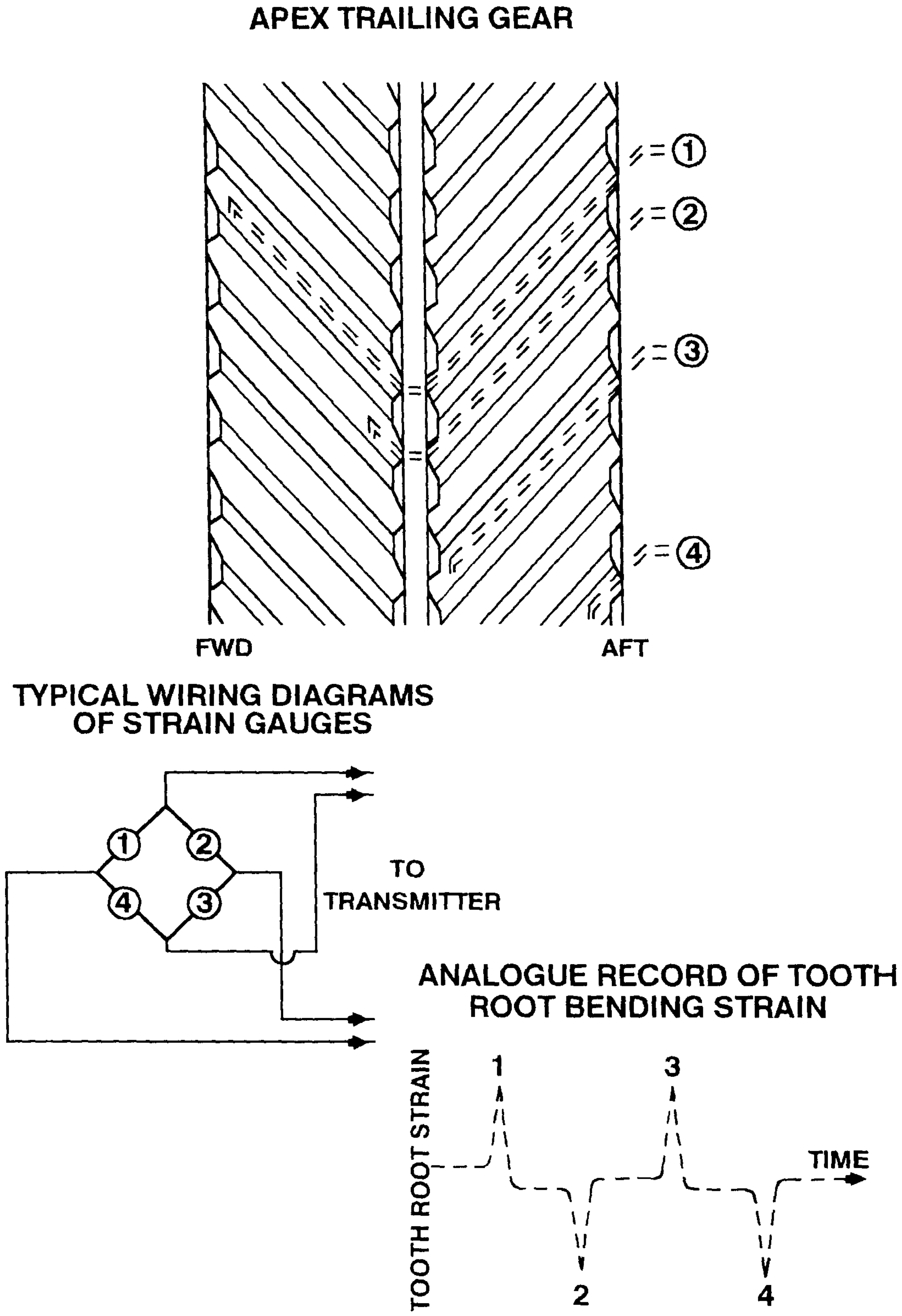


FIG. 8—GEAR TOOTH STRAIN MEASUREMENTS