# THE MODULAR ENGINE

## CONCEPT AND CONTROL

BY

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### Introduction

The Gem, the Royal Navy's first fully-modular gas-turbine engine, is now being introduced into service. It powers the Lynx helicopter, which will replace the Wasp in ships' flights, and it is therefore timely that the modular concept in gas turbine engines should be described. The purpose of this article is to explain the concept, illustrate its advantages and disadvantages and consider the question of administrative control. The gas turbine engine is no longer confined to the world of aviation, and so modularity is considered in a general sense except where reference to the Gem lends clarity.

### The Modular Concept

A modular engine is one in which the basic functional sections are designed and manufactured as discrete units—modules—capable of easy replacement with minimal proof testing. In gas-turbine engines the modules normally comprise gearboxes, compressors, and turbines. External engine pipework and electrical harnesses are not usually considered part of the various modules, but as separate items to be added after module assembly. Modules are made to tight tolerances to ensure their satisfactory interchangeability in engines both in the physical and aerodynamic senses. This means an engine may be assembled with confidence from any selection of appropriate modules with mixed running hours. This easy module change facility allows the rapid repair of engines in the field and renders unnecessary the return of the majority of complete engines to the repair organizations. As only modules need to be returned it is absolutely essential that individual control of them is exercised and the concept of an engine as an indivisible single unit no longer applies.

The modular concept of engine design was developed first in aero-engines, for financial reasons. Aircraft gas turbines are very expensive; aircraft power plants, for instance, commonly account for a quarter of the total aircraft cost. An aircraft operator must not only purchase engines to install in the aircraft, but also a considerable reserve if the required aircraft availability is to be maintained. Repairs and routine overhauls add further expense. Aircraft operators and engine manufacturers alike sought means of making more cost-effective use of the money needed for the purchase and support of engines and the fully modular engine has resulted. The Gem is the first naval example.

### The Gem as a Modular Engine

The modular concept is clearly illustrated in the description of the Gem engine and the plans for implementing its introduction and control in the Fleet Air Arm.

In the Lynx, two Gem engines are mounted side by side aft of the main rotor gearbox in separate compartments. Each engine drives through a front-mounted reduction gearbox. The engine is a free turbine turbo-shaft with a two-spool compressor and a reverse-flow annular combustion chamber. Its maximum continuous power rating is 750 shp with a 900 shp rating for $2\frac{1}{2}$ minutes. It weighs less than 400 lb and is about 43 inches long.

The Gem comprises seven discrete modules pictorially represented in FIG. 1. FIG. 2 diagrammatically shows their assembly to form the engine:

FIG. 1—THE GEM ENGINE—SEVEN MODULES

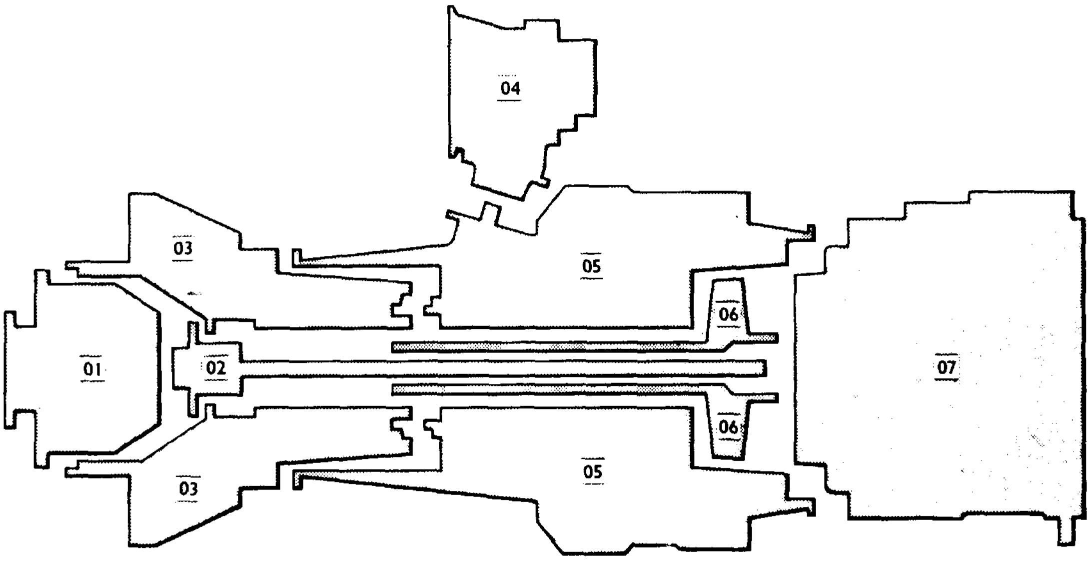


FIG. 2—THE GEM ENGINE—DIAGRAMMATIC ARRANGEMENT OF MODULES

*Reduction Gearbox (Module 01)*: Located on the front of the engine, the reduction gearbox is mounted within the hub of the air intake and provides an engine speed reduction of approximately 4·5 to 1.

*Free Power Turbine Shaft (Module 02)*: This shaft transmits the drive from the free power turbine, through the centre of the engine to the reduction gearbox. Incorporated in it is the phase-displacement torque-measuring system, operating on the principle of measuring the twist along a calibrated section.

*LP Compressor and Intake (Module 03)*: This module comprises a four-stage axial LP compressor and the annular air intake, the latter accommodating the reduction gearbox (M01).

*Accessory Gearbox (Module 04)*: The accessory gearbox is mounted on and driven by the HP spool module. Mounted on module 04, although not defined

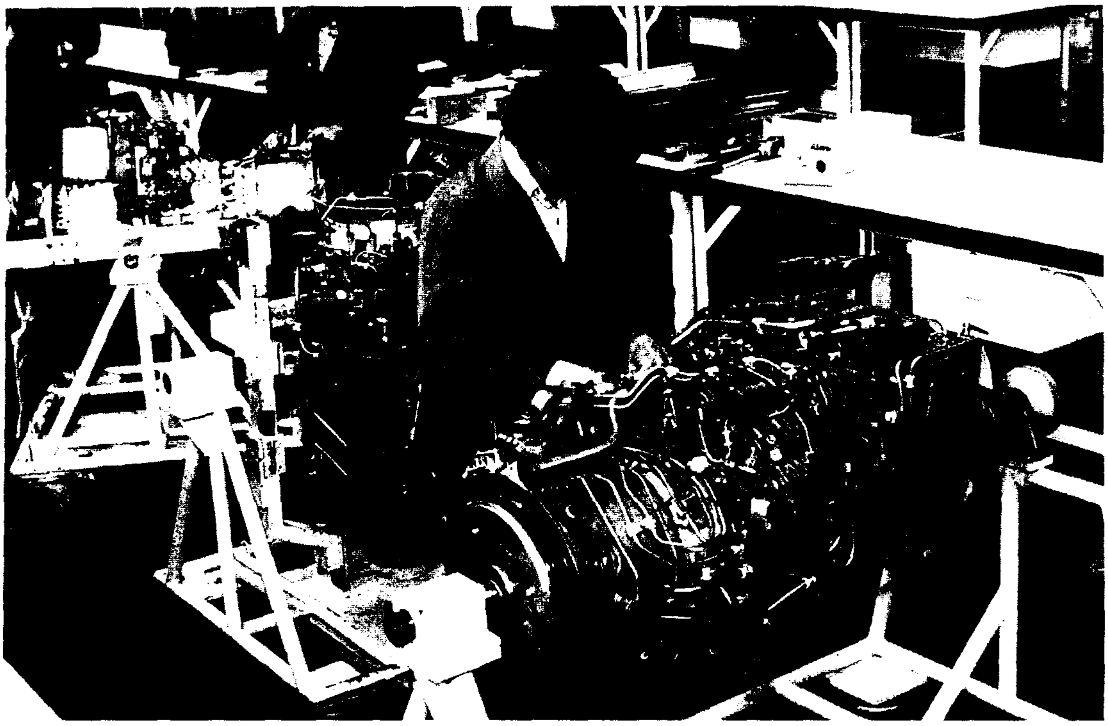

FIG. 3—THE GEM ENGINE—'DRESSING' THE ASSEMBLED MODULES

as part of it, are the oil cooler and fan, starter/generator, fuel flow control unit, and the number three aircraft hydraulic system pump.

*HP Spool and Combustion Section (Module 05)*: In this module the air from the LP compressor is further compressed, mixed with fuel, and burned. M05 contains the radial HP compressor, the annular combustion chamber, and the HP turbine.

*LP Turbine (Module 06)*: This provides power to drive the LP compressor and consists simply of a single turbine wheel and shaft. The LP nozzle is contained within M05.

*Free Power Turbine (Module 07)*: This is the rear module of the engine and includes the free power turbine rotor and nozzles and the exhaust casing.

Each Lynx-operating ship will carry one spare Gem engine. Module changes are not yet permitted at this level of servicing (First line) and defective whole engines will be returned to either R.N.A.S. Portland or Yeovilton (Second line), which are the designated bases with servicing facilities for the Gem. Here defective modules will be replaced and engines test run ready for re-issue to the First line. Defective modules will be sent to R.N.A.Y. Fleetlands or Rolls-Royce Ltd. (Third and Fourth line respectively) for repair or overhaul and subsequent return to Second line. There will be exceptions to this procedure as shown in FIG. 4. For example, some engines will need to be returned complete for defect investigation by Third/Fourth line establishments or, perhaps, an engine immersed in salt water at First line would require speedy despatch direct to the repair organization. These are shown by the broken lines but the solid lines in FIG. 4 represent at least ninety per cent. of engine/module traffic.

The implementation of a module replacement policy at Second line requires provision of test running and diagnostic facilities. R.N.A.S. Yeovilton and Portland will each be established with a Gem Engine Test Stand (GETS) for these purposes. Whilst not being quite as sophisticated as the Third/Fourth line test beds, the GETS will be sufficiently instrumented to permit both the conduct of full performance checks on assembled engines and the isolation of engine defects to specific modules. To ensure consistency of results between Second and Third/Fourth line, the GETS will be routinely checked with specially calibrated engines. These test facilities can be moved and have been designed to allow for air transport on standard sized pallets.

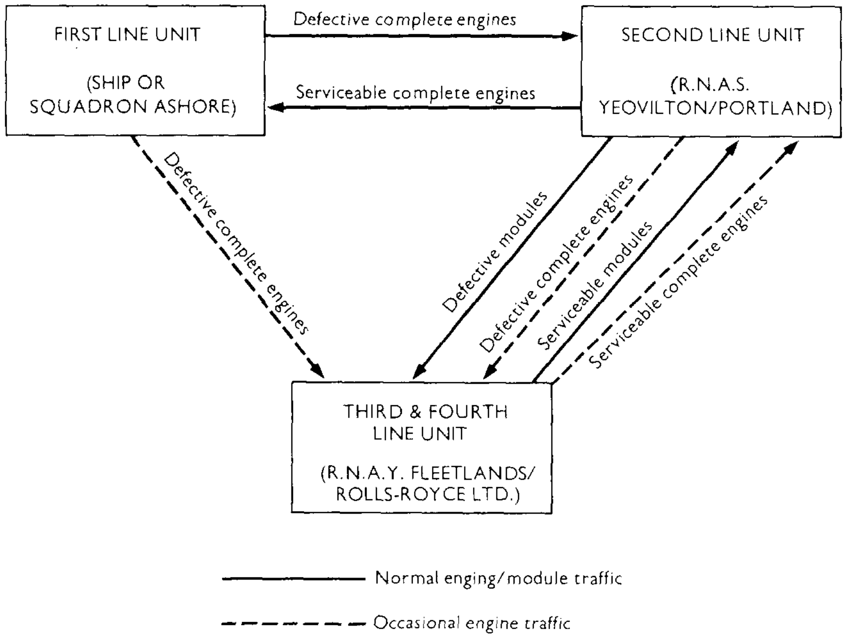


FIG. 4—ENGINE AND MODULE TRAFFIC PATTERN

## The Advantages of Modularity

These may be summarized as:

(*a*) More cost-effective use of capital expenditure.

(*b*) Reduction in through-life costs.

(*c*) Improved engine availability.

*More Cost-Effective Use of Capital Expenditure*

In any gas turbine engine some elements are more prone to defects and have shorter permitted overhaul/fatigue lives than others. The 'hot' rotating components are in these categories, 'cold' components tend to be more reliable and have longer lives. In the Gem, the module M05 (HP spool) can be expected to be less reliable and to have a shorter time between overhauls than, say, the reduction gearbox (M01). Clearly, it would be prudent to concentrate more of the financial resources on M05 than M01. This reasoning can be applied to all modules. Having purchased sufficient engines for installation, the money for reserve engines may be split up into a purchase of individual modules, the quantity of each depending on the predicted failure rate. A more cost-effective use of capital is made by buying more of the modules with shorter predicted achieved lives and less of those not so prone to defect. The correct determination of the quantities of each module required is crucial to the successful long-term operation of modularity. It is a complex exercise and is described later.

*Reduction in Through-Life Costs*

In non-modular engines, when one of the main elements is defective or due for overhaul, the complete engine is usually returned to the repair organization and then remains out of service for some months. With a modular engine only the defective modules are returned, the remainder being retained in service available for further use. This reduces costs in several ways.

(*a*) as only the defective modules are returned for repair/overhaul, those remaining in service can be used to their full overhaul lives (barring defects), maximizing their utilization;
(*b*) overhaul is limited to those sections of the engine requiring it at the time;
(*c*) transport costs are minimized;
(*d*) as only the particular sections of the engine which require repair/overhaul are seen by the overhaul base, stripping and assembly of complete engines is avoided;
(*e*) Repair organizations must issue repaired engines with a significant remaining overhaul life. This necessitates the premature replacement of many serviceable components when complete engines are returned. The return of defective modules minimizes this.

*Improved Engine Availability*

Inevitably, during service life of an engine type, occasions arise when insufficient engines are available to meet the demand. It is not cost effective to plan to avoid these peaks entirely as more engines would need to be purchased than would otherwise be required. Such shortages are less likely to be experienced with modular engines because:

(*a*) a serviceable engine can be obtained from two or more unserviceable ones by 'swopping' modules between them if different items are defective;
(*b*) the tempo of the in-service module changing base can be made responsive to the needs of operational units, increasing engine turn out when necessary;
(*c*) more of those modules predicted to be less reliable will have been purchased in the first place.

**The Disadvantages of Modularity**

These may be summarized as:

(*a*) Increased cost of development.
(*b*) Extra cost due to modifications.
(*c*) The difficulty in predicting spare module requirements.
(*d*) Complexity of administrative control.

*Increased Cost of Development*

Significant financial advantages accrue from the purchase and operation of modular engines, but the modular facility adds to the development and purchase costs of an engine. Extra design and development work is needed to guarantee the physical and aerodynamic interchangeability of modules. Because the modules must be capable of easy replacement in workshops lacking the comprehensive equipment and specialized knowledge of a repair organization, module interfaces must be precise, imposing restrictions on engine design. In production, manufacturing tolerances must be more closely controlled to preserve interchangeability than would otherwise be necessary.

It is difficult in retrospect to define the extra costs peculiar to a modular engine, but these must be substantial. It might be argued that the money spent on developing a modular engine could be better used in purchasing larger numbers of the same engine, but developed without a modular facility. Certainly if there was sufficient money to provide many spare engines, a modular engine would not be required, but this would not alter the case that modularity must give the operator significant operating savings and a reduced capital investment.

*Extra Cost due to Modifications*

If the benefits of the development of a modular engine are to be fully realized, complete module interchangeability must be retained throughout its service life. Provided that modifications are contained within one module, interchangeability of modified and unmodified modules within an engine will not be affected. If, however, other engine modules require concurrent modification to remain compatible with the first, interchangeability problems arise. In this case it is necessary to modify speedily all affected modules to return the engine fleet to its fully interchangeable modular state. To achieve this it may be necessary to return serviceable modules to the repair organization for modification at the expense of additional traffic between the servicing base and overhaul facility and a temporary reduction in the number of spare modules available. Fortunately the number of modifications which give rise to interchangeability problems is usually small.

*Prediction of Requirement*

Determination of the reserve engine requirement for a non-modular engine is relatively simple and can be conducted manually quite adequately. The principal factors which affect the result are the predicted changes in engine premature rejection rate, the overhaul life progression pattern, and the time out of service during repair or overhaul. Calculations performed at intervals during the forecast period will indicate the quantity of reserve engines needed to maintain the required availability.

A modular engine introduces substantial complications to these calculations. Each module has its own predicted premature rejection rate and overhaul life progression pattern. Because every module is at some risk of damage from the failure of any other module in the engine, a matrix of secondary damage probabilities must be derived and included in the calculations. The fact that engine repair by module change takes place at different locations to the repair of modules also has to be considered, together with the probability of whole engines having to be returned to the repair organization. The time out of service for each module during repair or overhaul is also different. The inter-relation of so many factors makes the services of a computer essential.

The use of a computer for analysis permits the inclusion in the simulation of other minor variables which would not be considered as having a sufficiently significant effect to warrant inclusion in a manual calculation. Examples are variations in transit times of engines and modules between bases and units due to their location and variations in usage rate during the year (particularly applicable to aircraft, as flying is usually less intense in the winter months). A mathematical model is prepared to simulate the engine fleet's mode of operation and several computer runs are conducted for the forecast period, usually about ten years. The results, within suitable confidence limits (commonly ninety per cent.), provide the engine and module requirements.

*Complexity of Administrative Control*

As a modular engine cannot be considered an entity, control must be exercised over the individual modules. This is in addition to the continued need to control the allocation of assembled engines and it magnifies the control task. For instance, with a joint Royal Navy/Army purchase of some 500 Gem engines (which the Royal Navy is required to administer), the number of modules in existence will be of the order of 3500. It is necessary, when assembling engines, to select modules with similar remaining overhaul lives to avoid frequent engine removals for module change. There is also a need to ensure that module modification states are compatible. In addition some degree of control must be applied to those parts of the engine which are not defined as part of any specific module. Thus modularity presents the controlling authority with a larger and more complex task than would otherwise exist.

## Administrative Control of Modular Engines

*Control of Modules*

With non-modular engines, a controlling authority's basic task is to allot engines to the user vehicle or to the selected repair/overhaul base. In the former case the engine modification state must be suitable for its intended use and the life remaining to overhaul must be adequate. These requirements apply equally to an assembled modular engine, but in addition the modules selected to form an engine must have compatible modification states and the most advantageous overhaul lives remaining. The need for compatiblity of modification states is obvious; the selection of modules by remaining overhaul life requires explanation.

To achieve the full benefits of modularity, two conflicting requirements must be rationalized: the minimizing of engine removals for the replacement of life expired modules, and the achievement of the maximum usage of module lives before their return for overhaul.

If an engine undergoing a module change were to be considered in isolation, the module in question would simply be replaced by another with a remaining overhaul life in excess of the specified minimum for engine issue. Provided the remainder of the engine modules also had lives to overhaul in excess of the minimum they would remain untouched. Consequently, the lives of engines returned to service after module change would tend towards the minimum allowable life remaining unless positive control were exercised over the module changing activity. This minimum figure, if set low, would result in an unacceptable average achieved life. Should it be set high, to avoid this, considerable waste of useful module overhaul life would occur.

The controlling authority therefore needs to exercise close control over module changing activities, optimizing the grouping of modules into engines to gain maximum value from modularity. This must involve not only the careful selection of modules to replace those removed for defect or life expiry but also the consideration of removing other modules so as to achieve improved module combinations.

Planning for cost-effective module control must pay due regard to the following principles:

(*a*) Routine module replacement decisions must be taken against the broadest possible background of the current engine fleet state. The aim must be to ensure that these daily decisions are arrived at in the light of the best possible prediction for the immediate future.

(*b*) Individual module replacement decisions must be taken in the context of an overall long term plan for either:

(*i*) maximizing the total installed engine life at all times; or

(*ii*) minimizing the waste of unused module overhaul lives; or

(*iii*) some compromise between (*i*) and (*ii*).

To achieve the best possible combinations of modules in engines the long term module-changing programme would have to be based on knowledge of the remaining overhaul lives and modification states of all installed modules (to predict life expiry arisings), all those immediately available for installation, and those shortly to be rel ased from the repair organization (whose production plan for repaired/overhauled modules would be needed to ensure that work priorities accorded with the controlling authority's requirements). The programme developed would require frequent and rapid revision as unforeseen (i.e. defect) arisings occurred.

*Control of Extraneous Items*

A modular engine can be designed in two ways. The basic carcase of the engine can be made up of modules with external pipework, cable assemblies, fuel system components, etc. being added after engine assembly and not comprising part of any module. Alternatively, the complete engine can be split into modules, with pipes, etc. dividing at the module interfaces. This latter option would ease administrative control, but is more costly in terms of engine development and support and is not favoured by either engine manufacturers or their customers. The engine operator must therefore consider whether or not to control those engine components which do not form part of any module.

Non-modular engines are periodically returned for overhaul in a complete state and the external items can then be inspected, cleaned and replaced as necessary. With a modular engine these external components may never be returned for overhaul, but simply be transferred from engine to engine at the module changing base. It is not normal, or desirable, to have separate documentation for such minor items (with the exception of fuel control unit components) and, as they are not associated with particular modules, their history will not be recorded. With a possible service life of an engine type of fifteen to twenty years, these components could miss any form of routine inspection for this period.

The considerations which affect the decision to control these components must be based on:

(*a*) the degree of hazard to the user vehicle resulting from any particular engine component failure and whether the risk of failures could be reduced if routine inspections would detect their onset;

(*b*) the cost involved in repairing damage to engines which might have been avoided if regular inspections would have detected incipient failures;

(*c*) the need for a knowledge of the life used by a component so that in the event of the future imposition of fatigue lives, unnecessary scrapping can be avoided.

The first of these considerations is essentially an engineering decision, the others financial. If the engine operator decides that routine inspections or the recording of expended life must take place, four methods of control are possible, namely to:

(*a*) consider the extraneous items as another 'module' with the appropriate documentation;

(*b*) consider what is left when the modules are removed as being the 'engine', also with appropriate documentation:

(*c*) identify and retain items with each of the modules;

(*d*) retain them all with one particular module.

The first two options require extra documentation and control. The second two avoid this complication, but require the purchase of additional components to allow the uninstalled modules to retain the extraneous components associated with them. If, to avoid premature scrapping of components of unknown history, the life expended on components must be known, then one of these options must be pursued. On the other hand, if it is considered not cost effective to record the life expended on these items, inspection of them whenever an engine is returned to the module change base would suffice. Depending on the items and depth of inspection necessary, extra facilities might have to be provided, but this would be preferable to the extra costs involved in inspection of these components at the overhaul base and the control procedure required to achieve this.

## Conclusion

The value of modularity to the operator is not in doubt. It provides significantly greater flexibility at reduced operating cost, with more cost-effective use of capital expenditure. Whilst this may be at the expense of greater complexity in control, it is a small price to pay for the enhanced engine availability provided. The extra development cost is unattractive but is unavoidable. The future of the modular engine is assured.

# ENGINE HEALTH MONITORING FOR R.N. GAS TURBINES

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## Introduction

Before discussing the various means of engine health monitoring (EHM) used in the Royal Navy for gas turbines, it is important first to answer three questions:

(*a*) What is EHM?

(*b*) Why use EHM?

(*c*) How to apply EHM?

Although almost bound to be subjective, depending on the type of operation of the gas turbine, the following definition of EHM may be assumed in the context of this paper:

> 'Engine health monitoring is the general term for all methods designed to give the operator an indication of a change in condition of systems or components relative to a condition of the particular system or component which is accepted as normal'

The mention of a 'change in condition' correctly indicates that EHM is a comparative method. A single set of readings of engine parameters does not in most cases give a clear understanding of the situation.

The objectives of EHM are:

(*a*) in the short term, to detect developing defects at a sufficiently early stage to prevent or minimize secondary damage;

(*b*) to assess the overall condition of the engine to assist the operator in making his decision when to exchange the engine.

This does not mean that all engine changes should be made 'on condition' instead of after a specified number of running hours. The R.N. believes that, both for operational and logistic reasons, engines must be removed after a certain time even though EHM indicates the condition of the engine to be reasonable. This time is called the declared overhaul life (DOL). Endeavours will be made, however, as experience is gained to make this time as long as possible. In fact, the present defined DOL infers that approximately 20 per cent. of the total number of engines will reach that life. For the other 80 per cent., EHM should serve to ensure their removal before catastrophic failure.