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SUMMARY

A set of advanced blading has been designed for a 5-stage high-speed research core compressor. The blade profiles were aerodynamically-tailored using a sophisticated S1-S2 flow calculation system, developed at RAE Pyestock, which incorporates an inviscid-viscous blade-to-blade code. The design and measured performance of the compressor are compared with an initial conventionally-bladed 4-stage version. The new design achieved a peak level of polytropic efficiency approaching 91%, a substantial improvement on the initial version.

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LIST OF CONTENTS

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1. INTRODUCTION

The main aim of the compressor research programme at RAE Pyestock is to develop improved aerodynamic design and analysis methods for axial-flow compressors, so that higher levels of performance can reliably be achieved. This methods development is complemented by a sequence of compressor design, manufacture, test and analysis; improved designs can then be produced and the sequence repeated. For core compressors, the process is centred around a high-speed multistage axial research unit, designated C147. This compressor is representative of the rearmost stages of a highly-loaded military or civil compression system. However, it is much larger than an engine unit and has extensive instrumentation, in order to allow detailed investigations of the internal flow, and its design provides maximum freedom for reblading. The initial 4-stage build of C147, which was a conventional design with a design pressure ratio of 4.0, has been described previously (1). This paper extends the discussion to the second build, which incorporates an additional front stage to raise the design pressure ratio to 6.4, and features completely redesigned blading with aerodynamically-tailored blade profiles. The blading design relied heavily on computations of the internal flow using a sophisticated S1-S2 calculation system developed at RAE Pyestock, in contrast to the correlation-based approach employed for build 1. The impact of this change in design methods is of particular interest.

The paper first summarizes the main features of C147 and then describes the S1-S2 flow calculation system used for the blading of the second build. This system involves interaction between blade-to-blade calculations, using the S1BYL2 inviscid-viscous code (2), (3), and a conventional streamline curvature S2 calculation for the pitchwise-averaged flow (4). The design approach is described in detail, including an example of the blade profile shapes and S1BYL2 flow predictions. The overall performance achieved on test is given; this indicated substantial improvements in efficiency relative to the first build, with a peak polytropic level at design speed approaching 91%. Finally, some post-test analysis is presented, and possible further improvements in the design approach and in the flow calculation methods are suggested.

2. MAIN FEATURES OF C147

The principal design parameters for the 4 and 5-stage configurations of C147 are specified in Table 1. It can be seen that the levels of exit Mach number, hub speed and hub/tip ratio are within current engine limits. Therefore the increased duty of C147 relative to current engine compressors has to be achieved by higher aerodynamic loading. The initial design of C147 described in (1) included both 4 and 5-stage versions, but only the 4-stage version was manufactured and tested as build 1. The completely rebladed build 2 incorporated the additional zero stage (stages are numbered 0 to 4).

A sectional drawing of the C147 compressor is shown in Fig 1. Particular attention was paid in the design of the compressor to maximise its value as a flexible research vehicle for the development and validation of blading design methods. The unit is

Table 1 Overall design parameters

	4-stage	5-stage
Pressure ratio	4.0	6.4
Mass flow (at 288K and 1 atm inlet)	33.2 kg/s (73.2 lb/s)	49.5 kg/s (109.2 lb/s)
Rotational speed (at 288K inlet)	6380 rpm	6894 rpm
Exit Mach number (metal annulus)	0.265	0.265
Exit hub speed when operated at 840K delivery temperature	360 m/s (1182 ft/s)	360 m/s (1182 ft/s)
Exit hub/tip ratio	0.912	0.912
Exit blade height	38.1 mm (1.5 in)	38.1mm (1.5 in)
Inlet tip diameter	0.892 m (35.1 in)	0.917 m (36.1 in)

much larger than typical engine HP compressors (typically twice linear scale) with larger-than-usual axial gaps (23 mm or about 50% chord) to enable extensive instrumentation to be inserted with minimal disruption to the flow. The rig has provision for aerodynamic traversing in the inter-row gaps (area traverses behind stators and radial traverses behind rotors). The casing also has provision for laser windows. In addition, the fixed blade rows are inserted in circumferential slots on relatively long platforms so that numbers and chords can be changed. Chordal Reynolds number for the zero stage rotor at the design, atmospheric, inlet condition is about 1.1 x 10^6. The overall mechanical design of the unit was undertaken at RAE Pyestock. A particular feature is the main rotor assembly; the complete drum with discs was machined from a single titanium forging, with the zero-stage disc bolted to the front. Tight tip clearances were targetted, and measured mean rotor clearances were just over 1% of blade height at design speed.

3. S1-S2 FLOW CALCULATION SYSTEM

3.1 General description

Considerable effort has been devoted at RAE Pyestock over recent years to the development and validation of an S1-S2 calculation system capable both of predicting the overall and blade row performance and internal flow of a wide range of compressors, and of being used as a design tool. This system has been applied successfully to transonic fans (5), (6). It was not available for the design of the initial build of C147, but was a vital element in the design of the rebladed 5-stage unit. It has also been applied to both builds in a post-test analysis mode to aid understanding of the measured results, and to provide a common basis for comparing the two versions, which adopted very different design approaches. These post-test analyses employed the latest version of the S1-S2 system, which is described below. It is a developed version of that used in the design of build 2.

The S1-S2 approach uses separate treatments to calculate flow in the hub-to-tip or meridional (S2) plane, and on a series of blade-to-blade (S1) stream-surfaces. The axisymmetric stream-surfaces used for the S1 analysis are defined by the S2 calculation, and the blade performance data for the S2 calculation are part of the S1 solutions. Thus, by iterating between them, a converged quasi-3D solution for the whole flow field can be obtained. The RAE method has been described in detail elsewhere (5). It incorporates an interactive inviscid-viscous S1 calculation, known as S1BYL2 (2), in which the blade surface boundary layers and wake are modelled by an integral treatment involving laminar and turbulent regions with instantaneous transition between. S1BYL2 predicts blade section deviation angle, profile and shock loss in addition to details of the flow field. Experience indicates that predictions are generally reliable for blade sections operating near optimum incidence, but that the significant increase in loss which occurs as the incidence angle increases and the section stalls is not automatically predicted (3). Improved predictions can be obtained at off-design incidences by assuming fully turbulent boundary layers, but this is of limited applicability because results depend critically on the choice of starting condition for the boundary layer calculation, and no clear guidelines for the choice yet exist.

For calculating the S2 flow-field in multistage core compressors, a streamline curvature method is employed. This is a simplified version of that described in (4). The full radial equilibrium equation is solved at all calculating planes, but it is considered that the extra complication of having calculating planes within the blade rows is not generally necessary for a core compressor where the hub/tip ratios are fairly high and the blade rows operate mainly subsonically and unchoked. Therefore the program is run in the 'ductflow' mode, with calculating planes placed at the blade leading and trailing edges only. Linear variations of stream-surface radius and stream-tube thickness are assumed within the blade rows for the S1 calculations. The blade performance data, consisting of exit flow angle and profile loss coefficient, are derived from the S1 solutions via a wake mixing calculation carried out on the downstream boundary of the S1 domain.

End losses, arising from secondary flows, annulus wall boundary layers and tip clearance, are not predicted from the S1-S2 treatment currently adopted. Therefore appropriate radial distributions of extra loss must be specified as an input. This loss, together with annulus blockage, represents the only empirical input required to the S1-S2 calculation system. However additional empirical input eg deviation corrections, can be included where necessary; for example in post-test analysis to match S1-S2 solutions more closely with test measurements.

Appropriate distributions of annulus blockage and blade end loss have been determined from analysis of a number of multistage compressors at RAE. End losses are assumed to be proportional to the mean profile loss of the blade row in question and, since the S2 calculation does not include a spanwise mixing mechanism, these are spread across the whole span (using a parabolic distribution). The resultant total loss coefficients are typically twice profile loss at mid-span, and rise by about 65% towards the blade ends. A blockage allowance which increases by ½% per blade row for the first few stages is generally appropriate, with the inlet blockage being chosen according to the particular test installation. For C147 a blockage value of 2% is adopted at inlet to the first rotor, increasing over the first 4 stages and then remaining constant. Blockage is represented by a 'distributed' blockage factor enabling the true metal annulus to be used.

The S1BYL2 calculations, which are carried out on a sheared H-grid, employ uniform axial and tangential spacing within the bladed region, generally with 51 axial and 16 or 21 tangential points; further points are used to extend the calculation domain by about 0.8 axial chords upstream and downstream. Constant values of the gas specific heats are set for each blade row according to the local conditions. The turbulence levels assumed correspond to an inlet relative value of 5% throughout the machine. In the S2 calculation eleven quasi-streamlines are employed, equally spaced across the annulus height. The calculating planes are leaned (non-radial) but straight and positioned to give a close fit to blade leading and trailing edges throughout the machine.

3.2 Application to build 1

For build 1 of C147, a post-test S1-S2 analysis at design speed, near the peak efficiency operating point, matched the measured overall mass flow and pressure ratio (which were both about 3% higher than design intent) almost exactly (1). It also gave good agreement with the stage pressure ratio distribution indicated by interstage traversing. The predicted overall polytropic efficiency was about 1% lower than the value of 89% achieved on test.

The predicted stage efficiency levels and radial profiles were broadly similar throughout the machine, in line with the simple loss model used. In contrast, the interstage traverse measurements indicated that stage efficiency levels fell through the machine and that there was a progressive change in the shapes of radial profiles, from a profile for stage 1 which showed losses to be concentrated near the end walls, to much flatter profiles in the rear stages. This effect shows the impact of spanwise mixing, which progressively distributes the end-wall losses across the blade span and eventually leads to the 'repeating stage' situation.

It was concluded in (1) that the addition of a mixing mechanism to the S1-S2 system was needed to improve the prediction of the radial variation of flow parameters. However, examination of the detailed blade-to-blade results indicated that there was considerable scope for improving the aerodynamic performance of the circular-arc profiles used on build 1. Worthwhile increases in the already-high levels of efficiency appeared feasible. It was thus decided to undertake a blade profile redesign exercise using the current familiar system, prior to the development of improved flow modelling.

4. DESIGN PARAMETERS OF BUILD 1 AND BUILD 2

4.1 Stage parameters

The stagewise distributions of Va/U (axial velocity/ mean blade speed), $\Delta H/U^2$ (enthalpy rise/mean blade speed squared) and pressure ratio for the initial design are given in Fig 2. The values for build 2 were very similar, apart from slightly lower levels of $\Delta H/U^2$. The axial velocity was kept as high as possible over the front stages in order to ease the loading. It was then reduced rapidly in the last two stages where the annulus is nearly parallel in order to drop the Mach number at exit to the design value. The loading parameter $\Delta H/U^2$ follows the same trend as the axial velocity, with the last stage significantly off-loaded to compensate for the lower inlet velocity and increased diffusion. The axial work distribution is similar, since the mean blade speed is nearly constant, and this results in stage pressure ratios varying from 1.61 for the zero stage to 1.28 for stage 4.

The selection of stage reaction is a compromise in several respects and different choices were made for the initial and rebladed designs of C147, as shown by the mean stage inlet flow angles given in Fig 2. The initial design employed a level of reaction near 50% (ie equal pressure rise in rotors and stators) for the subsonic rear stages. This gives a balanced blading design with similar inlet relative Mach numbers and flow deflections for rotors and stators, but the high interstage swirl angles which result mean that an extra outlet guide vane row is needed to turn the exit flow to the axial direction. For the front stages, which have higher axial velocities and tip speeds and lower temperatures, use of a similar level of reaction would give near-sonic blade inlet conditions. While this is acceptable for rotors, it is considered risky for stators. Reducing the stage inlet swirl angles ie increasing the reaction, lowers the stator entry Mach numbers while increasing rotor values. On the initial design this enabled the maximum stator inlet Mach number (which occurs at the hub end) to be limited to 0.8. However, for the rebladed version it was decided that slightly higher values of inlet swirl could be tolerated in the front stages, because this eased the rotor design task without making the stator design significantly more difficult. Then, by maintaining this level of interstage swirl throughout the machine and allowing 5° of residual swirl at delivery, the need for a double stator row at exit was removed.

Both designs employ an inlet guide vane row to give the desired pre-swirl. For the 5-stage version the stagger angle of this row is remotely variable, while the angles of stator 0 and the 4-stage IGV are settable. The IGVs and stators are unshrouded, apart from stator 0 of the 5-stage version.

4.2 Blading parameters

The streamline curvature calculation referred to previously was used to determine the design-point flow vectors for both versions of C147. The treatment of annulus wall boundary layer blockage for the two differed in detail, but was broadly similar to that adopted for the S1-S2 post-test analysis.

The two designs differed significantly in the methods used to estimate loss and deviation. The initial design used an established blading correlation for deviation and a radial correction varying linearly between +1° at the hub to -1° at the tip was added for rotors only. For the build 2 design, deviation angles predicted by S1BYL2 were used directly. The losses used for build 1 were based on a correlation derived from the Howell multistage compressor prediction method (7), with an arbitrary increase of just over 25% to give a more reasonable design-point polytropic efficiency of 88%. For build 2, profile losses were based on S1BYL2 predictions, with extra losses derived from a rule similar to that described in Section 3.1. Again the values of loss coefficient were adjusted to accord with an assumed design-point efficiency; in this case a value of 90% polytropic was considered to be reasonable. For both designs the radial variation of loss was similar to that given by the current S1-S2 loss model. The radial distributions of work were chosen to produce flat radial profiles of total pressure at exit from each stage.

A further important difference between the build 1 and build 2 designs concerns the types of blade profile used. For build 1, the profiles had circular-arc camberlines throughout, with NGTE C7 thickness distributions being used for the IGV, stator 4 and OGV, and double-circular-arc thickness distributions being used elsewhere. Choice of blade incidences and space/chord ratios was guided by choke and stall margin calculations. Mean stall margins were typically around 3°, while choke margins increased steadily through the compressor from about 7-10% for the front stages up to 30% for the final stator. On build 2 the blade profiles were of more general form and little guidance was available from blading correlations. This meant that much reliance was placed on the aerodynamic judgement of the designer, guided by the S1BYL2 predictions.

5. DETAILED DESIGN OF BUILD 2

5.1 Blading approach

Although a fully consistent S1-S2 system was used in the design, the degree of interaction between the S1 and S2 calculations was low because, as discussed earlier, it was considered unnecessary to include interblade planes in the S2 calculation. Once the stage inlet swirl and pressure ratio distributions had been set, the main concerns were: a) to keep the S2 calculation consistent with the S1 profile and shock losses and the end loss model adopted; b) to maintain radially-constant stage pressure ratios, and c) to ensure that the mixed-out S1 exit flow angles agreed with the S2 values.

The blade profiles used for rotors and stators were set up using a geometric generator developed at RAE which has been described previously (6). Up to 4 circular arcs can be used to define the suction surface and the fourth arc can be parabolic if required. On C147 the full freedom given by this generator was not required, and profiles with suction surfaces made up of 2 or 3 circular arcs were adopted for stages 0 to 2, while profiles with single parabolic-arc suction surfaces were used for stages 3 and 4. All rotors and stators had pressure surfaces made up of two cubics, with continuous slope and curvature at the junction, and had trailing edge wedge angles of 5°. The maximum thicknesses of stator rows 1-4 and rotor 4 were reduced by 1% of chord compared with the initial design, but the maximum thicknesses of rotors 0-3 and stator 0 were unchanged.

The blade profile shapes at several spanwise positions on each blade row were developed in a process of iterative refinement using the S1BYL2 blade-to-blade code. Particular attention was paid to the behaviour of the suction surface boundary layer. Low values of profile and shock loss were sought, while avoiding extremes which might be over-sensitive, either to the accuracy of the prediction method or to the precise operating condition. Space/chord ratios were kept close to those of the initial design for the first 3 stages, but higher rotor values and lower stator values were needed in the rear stages because of the change in reaction. Apart from the outer region of rotors 0-2, where shock effects were of some concern and suction surface camber in the uncovered region had to be limited, the blade profiles were more forward-loaded than for the initial design. The proportion of camber in the first half of chord was considerably greater than with circular-arc profiles, especially in the rear stages.

The predicted reductions in loss were encouraging; typically profile loss coefficients were 25-30% lower than for circular-arc profiles. The S1-S2 loss model, which assumes that end losses are proportional to profile losses, leads to a predicted difference in efficiency between the original and rebladed designs of over 3%. As mentioned earlier, this was felt to be over-optimistic, and the design losses for build 2 were increased by about 10% to give a design polytropic efficiency of 90%.

5.2 Off-design considerations

Although only a single design point was used, the blading design for build 2 of C147 paid consideration to off-design performance in several ways, for example in the selection of camber distribution and in the choice of conventional space/chord ratios and low effective incidences (as assessed by predicted aerodynamic loading at the leading edge). The design was thus more conservative than would have been the case if the highest predicted level of design point efficiency had been targetted. Furthermore, the definition of the blading for stages 3 and 4 took account of additional S1BYL2 predictions for individual sections which were carried out at incidences 4° greater than the design value and with fully turbulent suction surface boundary layers. These computations influenced the choice of parabolic-arc suction surfaces for the last 4 rows.

Off-design performance, particularly axial matching at part speed, is strongly influenced by choke margin (that is, the excess flow capacity of the blade row). There is a danger that over-reliance on blade-to-blade calculations at design speed could lead to insufficient consideration of choke margin. However the new design, with incidence chosen as mentioned, gives an acceptable axial variation of choke margin. A row-by-row comparison with the initial design (with choke margin being assessed via predicted mean passage entry Mach numbers at design point) showed that the two were very similar. While the addition of the zero stage will tend to increase axial mismatching at part speed, this should be countered by the provision of a variable IGV.

5.3 Example of blade-to-blade aerodynamics

A useful way of illustrating the predicted improvements in blade-to-blade aerodynamics is to compare a parabolic-arc profile of the type used for the rear rows of build 2 with a circular-arc profile of the same space/chord, thickness/chord and flow turning, operating at the same inlet conditions. The duty is close to that of stator 3 at mid-height; both sections are set at zero effective incidence (which is a little lower than typical for build 2) and for simplicity have constant stream-surface radius, with no streamtube contraction or extra loss.

The results of the S1BYL2 predictions are shown in Fig 3; these include Mach number variations in the inviscid flow-field and integral parameters of the blade boundary layers. It can be seen that the high forward camber of the parabolic profile (which has a 3.5 to 1 variation in curvature along the suction surface) causes a more rapid and more persistent acceleration on the initial part of the suction surface compared with the circular arc case, and the peak Mach number is almost 0.1 higher. This high peak is immediately followed by a diffusion rate which is initially much steeper than for the circular-arc case but becomes progressively less severe in the covered passage and towards the trailing edge. The transition point is not significantly affected, remaining near 10% axial chord, but the greatest loading on the suction surface boundary layer now occurs much further forward - near the front of the covered passage, where the layer is thin and better able to withstand it. By this means, the boundary layer separation evident near 75% of axial chord for the circular-arc case (which is apparent from the rapid increase in displacement thickness δ^* and in shape factor $\bar{H}$ #

$\bar{H}$ is effectively the shape factor (ratio of displacement to momentum thickness) of an equivalent incompressible boundary layer

through and beyond its nominal 'separation' value of 2.8) is almost entirely avoided. Values of δ^* and $\bar{H}$ at the trailing edge are roughly halved, and the predicted mixed-out profile loss coefficient is reduced by about 30%. The predicted performance of the parabolic-arc profile remains good when operated at 4° higher incidence and with a tripped suction surface boundary layer.

Finally some insight into loss generation and reduction can be gained from comparing predicted values of momentum thickness for the two profiles. At the downstream boundary of the calculation domain, the wake momentum thicknesses for the two cases are, as might be expected, roughly proportional to their profile loss coefficients (ie differing by 30%). However, near the trailing edge the two cases have very similar values of (combined suction and pressure surface) momentum thickness; in broad terms viscous losses generated over the blade surfaces appear to be similar. Downstream, the momentum thickness for the circular-arc case increases by some 80% in the wake region, compared with about 30% for the parabolic case. Such increases in momentum thickness are at first sight surprising, but do appear to be broadly consistent with the momentum integral relationship. In simple terms, this relates the rate of change in momentum deficit in the wake to the product of displacement thickness and pressure gradient. In the present case considerable viscous blockage is generated at the blade trailing edge plane (10% of pitch for the circular-arc case), and this causes an adverse pressure gradient as it decays downstream within the S1 streamtube, which has constant thickness and is at constant radius. The predicted values of blockage and pressure gradient and the predicted changes in momentum thickness appear to be consistent.

While neither the S1BYL2 wake treatment nor the current analysis are exact, the results do appear to indicate that (for circular-arc aerofoils in highly-loaded turbomachinery at least) a significant proportion of the predicted profile loss is generated during mixing of the broad wake. Most of the improvement predicted for the build 2 design appears to arise from reduced levels of mixing loss, due to the thinner and almost unseparated wakes. The higher values of peak blade surface velocity, which according to the arguments of Denton and Cumpsty (8) should be the most significant factor and would tend to increase viscous losses, do not appear to be of so much concern.

6. MEASURED COMPRESSOR PERFORMANCE

Information on the test installation and instrumentation, and on the overall performance of build 1 of C147 is given in (1). In summary the 4-stage build exceeded its design-target flow and pressure ratio, each by about 3%, and achieved a very respectable peak polytropic efficiency level of just over 89% at a surge margin of 15% #. At 25% surge margin the polytropic efficiency was just under 87½%.

The overall performance of the 5-stage build 2 measured at 90%, 95% and 100% of design speed is shown in Fig 4. Nominal inlet conditions were 0.9, 0.8 and 0.7 bar at 90%, 95% and 100% speed respectively, and the IGV was closed by 10° from its datum setting at 90% speed and by 5° at 95% speed. Notable features of build 2 are the wide flow range, which is similar to that achieved by build 1, and the flat pressure ratio characteristics above peak efficiency, particularly at design speed.

Build 2 achieved a peak efficiency level at design speed over 90½%, some 1½% greater than for build 1, but the peak efficiency point was 1% low on flow and 6% low on pressure ratio compared with design intent. The maximum flow passed just equalled the design value. The surge line shown on Fig 4 corresponds to a surge margin of about 10% at the design speed peak efficiency point. Efficiency remains high at 25% surge margin, the value being just over 89½% polytropic - over 2% greater than the corresponding value for build 1. However, the pressure ratio at this operating condition is only 5.5, compared with a value of about 5.9 which would have been reached if the design point had been achieved with a nominal 10% surge margin. The performance at 95% speed is worthy of note, with a peak efficiency level close to 91% polytropic being achieved in conjunction with a surge margin of 23%.

The very high levels of efficiency achieved by build 2 of C147 are extremely encouraging, and underline the potential of the design approach adopted. The deficit in pressure ratio is disappointing, and would obviously be of concern for a project compressor. However, the stage matching appears to be good and the deficit does not substantially detract from the value of build 2 as a research vehicle. Obviously the reasons for the deficit must be understood as part of the continuing process of improving the design methods. Analysis of traverse measurements, obtained using both conventional steady-state and high response instrumentation as well as laser anemometry, is in hand and post-test analyses have been carried out using the S1-S2 system, as for build 1.

7. POST-TEST S1-S2 ANALYSIS

On build 1, a good prediction of the overall performance (apart from a 1% underprediction of efficiency) was achieved without any adjustments to the parameters of the S1-S2 system (1). For build 2, some adjustment was needed to cater for the shortfall in pressure ratio. Following examination of the measured and design-intent stage performance, which indicated that no particular stage or group of stages was responsible for the deficit, it was decided to incorporate a 1° deviation correction on every blade row. The overall performance after this adjustment, predicted by an S1-S2 solution set up at the test inlet condition of 0.7 bar, achieves a close match to measurement, as can be seen in Fig 4. (The design inlet condition was 1 bar and other S1-S2 analyses indicate that the change in Reynolds number affects the pressure ratio by about 2½% and the efficiency by about ½%.) Because the predicted pressure ratio is very sensitive to the assumed value of mass flow, individual solutions can be misleading and so further S1-S2 solutions (not shown here) have been produced to match the measured pressure ratio characteristics over the full flow range. Similar solutions have been produced for build 1. Further empirical adjustments were needed for both builds, specifically concerning the selection of starting conditions for the fully turbulent suction surface boundary layers which are used to give improved blade-to-blade modelling for sections operating at high incidences. This work

Surge margin is expressed as (Rsurge - R)/ (R - 1) x 100% where all pressure ratios, R, are measured at the same mass flow

indicates that, in addition to the deviation discrepancy, the performance of the forward-loaded profiles used on build 2 shows a more rapid deterioration as incidence angle is increased, compared with circular-arc profiles.

From a practical viewpoint, the post-test analysis indicates that some refinement of the tailored profiles used on build 2 and some reduction in space/chord ratio may be beneficial. More significantly however, it appears that blade profiles of the type adopted should be set at lower effective incidences than corresponding circular-arc profiles (ie with lower aerodynamic loading at the leading edge), to compensate for the more rapid performance deterioration with increasing incidence. To guide the optimisation of profile shapes and incidences of a future design, full S1-S2 calculations should be carried out at several operating points. This would be especially important for an engine application where a specified surge margin target has to be met. With this approach, together with use of a deviation correction and allowance for the sub-atmospheric inlet condition, it is anticipated that design-intent pressure ratio and an increased surge margin could be achieved without substantial penalty in efficiency.

The above measures would permit improved designs to be produced with the current S1-S2 system. However, it is highly desirable to develop the system further so that the measured performance characteristics can be predicted without empirical adjustments. The analyses discussed above focus attention on improving the S1 treatment to improve accuracy at off-design conditions and to avoid the need for deviation corrections which vary with blade profile type. Such developments are in hand, although improving the predictive accuracy of the method to better than ±1° on deviation will be challenging. As regards the S2 treatment, it is recognised that the known shortcomings in predicting the radial variation in flow parameters may be a significant factor, and these must also be tackled. Consequently the S2 calculation has now been modified to incorporate a spanwise mixing mechanism, and improved treatment of blade/end wall effects is also in hand.

8. CONCLUSIONS

A second build of the C147 core research compressor, with advanced blading and an additional zero stage compared with the initial 4-stage version, has been designed and tested at RAE Pyestock. Particular aims are to investigate the performance potential for highly-loaded rear stages of blading with aerodynamically-tailored profiles, and to assess the impact of basing the design on S1-S2 flow calculations, instead of the blading correlations used previously. The measured performance of the new design was extremely encouraging, with a peak polytropic efficiency approaching 91% being achieved at design speed, at a surge margin of 10%. Corrected to a common inlet condition, the peak efficiency level is about 2% higher than for the conventionally-bladed 4-stage initial design. A similarly high level of efficiency was achieved at 95% speed with a surge margin greater than 20%.

The maximum flow passed by the compressor at design speed just equalled the design value, but the unit fell substantially short of its design-intent pressure ratio. Post-test analysis has indicated a modified design approach which should enable the shortfall to be recovered without significant penalty elsewhere. In addition improvements to the S1-S2 flow calculation system are in hand to improve its accuracy, particularly in the blade end regions and at off-design operating conditions. These developments should provide scope for further performance improvements and enable design-intent performance (including a target surge margin) to be achieved more closely on first test, as well as allowing more adventurous duties to be tackled.

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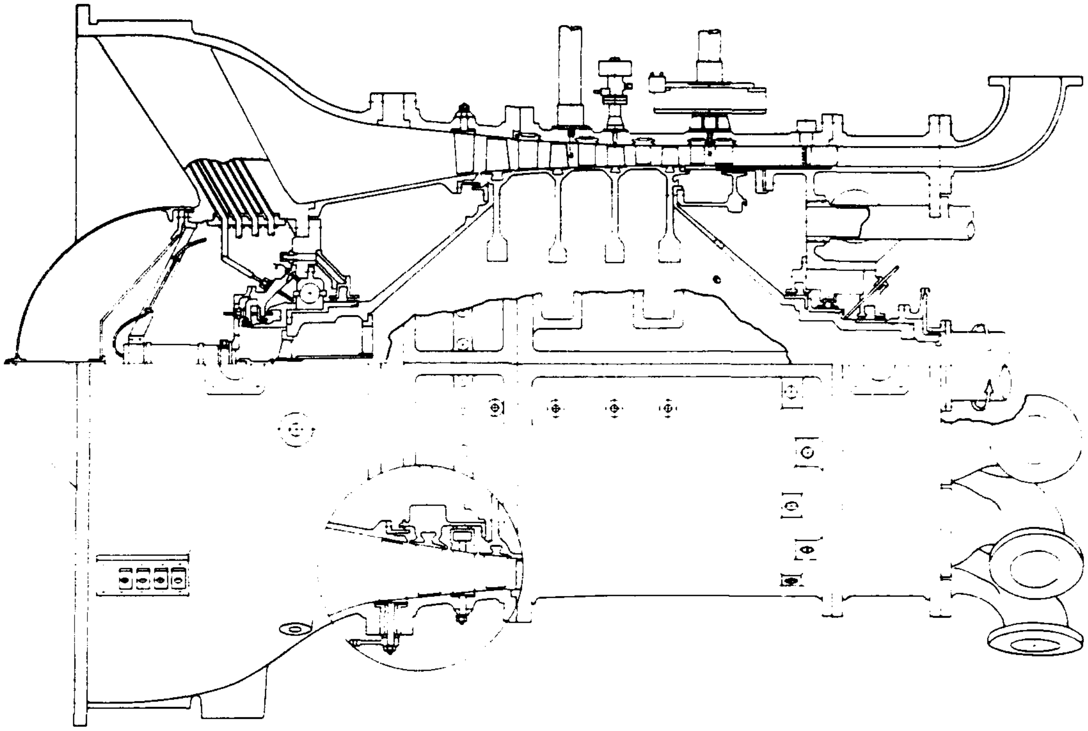

Fig 1 C147 compressor

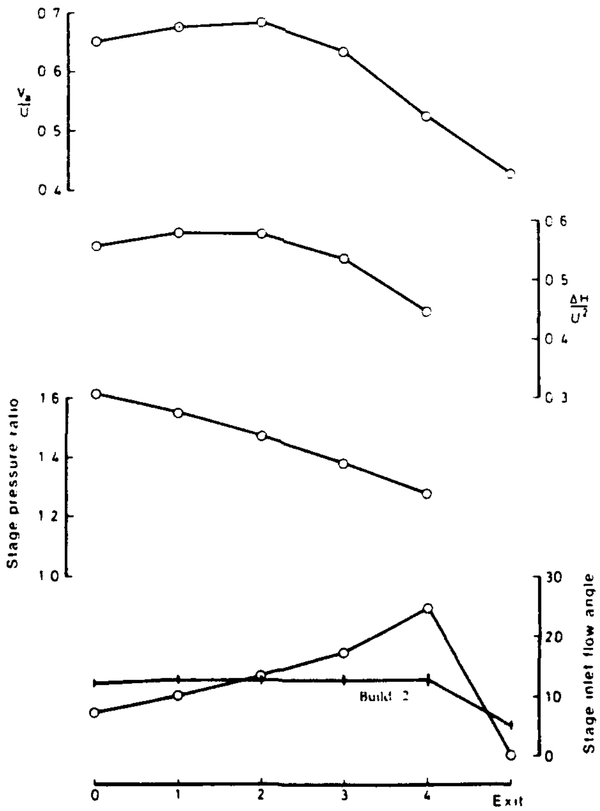

Fig 2 Stage parameters

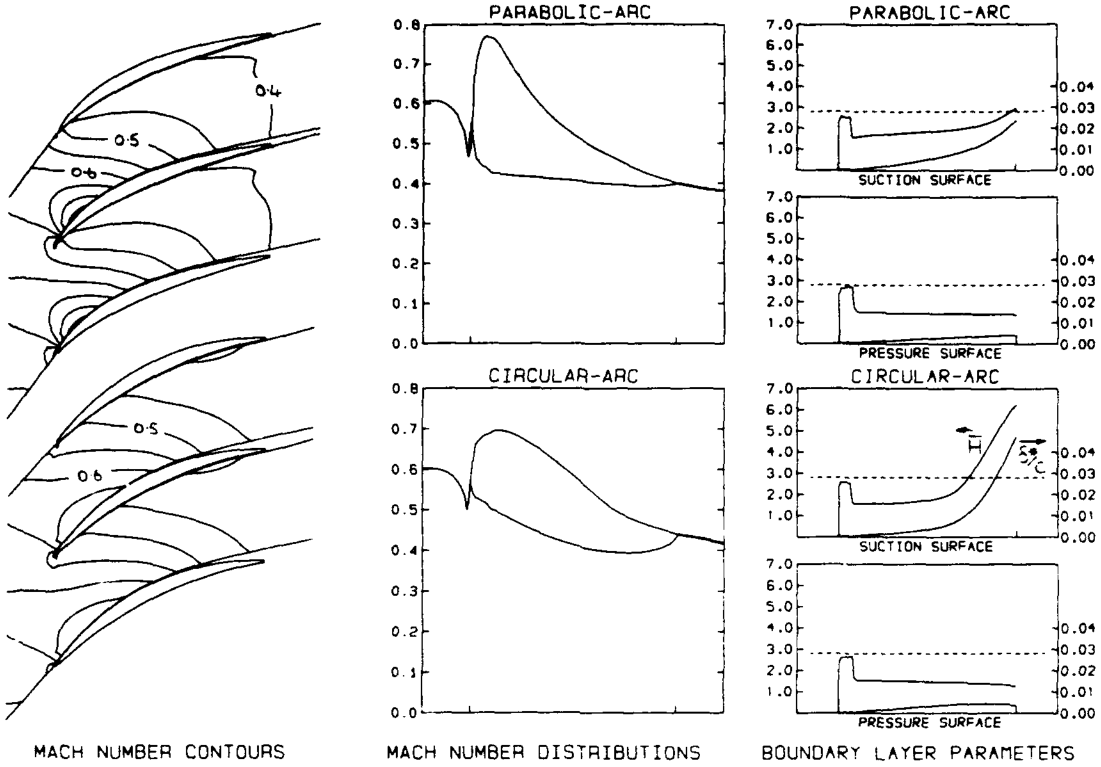

Fig 3 Performance predictions for parabolic and circular-arc profiles

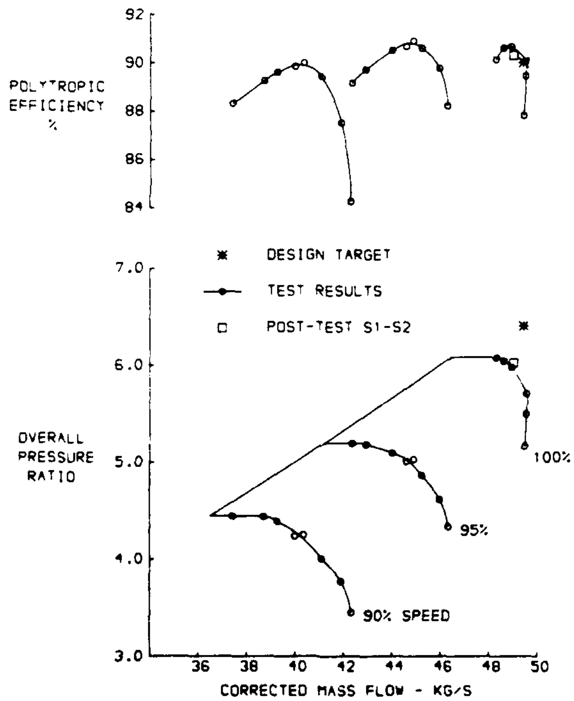

Fig 4 Overall performance of C147 build 2

REPORT DOCUMENTATION PAGE

Overall security classification of this page

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(1) Ginder, R.B. (2) Britton, A.J. (3) Calvert, W.J. (4) McKenzie, I.R.I. (5) Parker, Judith M			November 1990	10	8

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15. Distribution statement

(a) Controlled by – DRIC

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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Axial flow compressors*. Turbomachinery*. Compressor design. C147.

17. Abstract

A set of advanced blading has been designed for a 5-stage high-speed research core compressor. The blade profiles were aerodynamically-tailored using a sophisticated S1-S2 flow calculation system, developed at RAE Pyestock, which incorporates an inviscid-viscous blade-to-blade code. The design and measured performance of the compressor are compared with an initial conventionally-bladed 4-stage version. The new design achieved a peak level of polytropic efficiency approaching 91%, a substantial improvement on the initial version.

FS910/1

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