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A CASE STUDY OF IDEATIONAL FLEXIBILITY IN INNOVATIVE CONCEPTUAL DESIGN

William Lewis[1], Bruce Field[2] and John Weir[1]
[1]The University of Melbourne, Australia
[2]Monash University, Australia

ABSTRACT
The paper presents and discusses aspects of the responses of student engineering designers to an innovative conceptual design problem in kinematics: the design of a three dimensional mechanism required to ensure the successful operation of axial flow turbomachinery. The focus of the research was the development of design ideas and argumentation by individual designers, their capacity for thinking flexibly when generating different classes of proposal and when handling different lines of concept development as they explored the potential embodiments of different working principles. It was found possible to represent each designer's sequences of ideas and argument by means of a branching tree-like structure, as each new proposal evolved through the progressive solution of problems and subproblems. Construction of these design trees enabled the measurement of designer performance in terms of flexibility of thinking and the capacity for elaborating the physical embodiments of alternative working principles. The ways in which individual designers identified the boundaries of the stated problem and how most, but not all, accepted geometrical symmetry as an implicit constraint were noted and discussed in the context of overall designer performance.

Keywords: Conceptual engineering design, design rationale, ideational flexibility

1 INTRODUCTION

1.1 Background and Scope
To penetrate the mysteries of the human mind is a daunting task. Yet in the field of engineering design it is a matter of common observation that some engineers have a distinctive intellectual aptitude whereas others do not. The motivation for the research programme of which this paper forms a part is the desire to throw light on the nature of this aptitude, and then with the knowledge so gained, to help develop selection processes by which engineers with superior design aptitude are recruited. In this paper we are concerned with the divergent phase of conceptual engineering design, wherein the designer endeavours to generate a wide variety of ideas as candidate solutions to the problem posed in the design brief. The paper continues research previously reported at ICED 05 [1]. Whereas the earlier paper examined macro aspects of designer performance, notably ideational fluency and sketching ability, we are now concerned with the development of design concepts, as revealed by designers' sketches and note books, paying particular attention to the flexibility of thinking exhibited by different designers, i.e. their ability to generate proposals based on a variety of working principles and engineering hardware. This investigation is based on an analysis of the responses of individual students of engineering design to a specific problem. The problem chosen is a generic one in the design of axial flow turbomachinery where rotating arrays of blades impart energy to a stream of fluid moving through an adverse pressure gradient. In axial flow compressors, for example, it is often necessary to change blade angle settings in the early stages of a multi-stage compressor in order to accommodate changes in flow rate, and thereby prevent premature separation and stalling of the flow over the blade surfaces and thus avoid compressor surge. To achieve this outcome a mechanism has to be designed to transfer motion (in three dimensions) from an input controller or actuator to the axes of the designated set(s) of blades.
The opportunity to undertake this investigation arose from an industry/university liaison between the authors and a senior design engineer in an aero-engine manufacturer. With the Company's permission

the design engineer briefed the authors on a problem of the type described in the preceding paragraph, a problem in compressor design which the Company had faced and a solution found and implemented, hereafter referred to as the case problem. The design brief was adapted to form the basis of an undergraduate project and presented to undergraduate students of engineering design at the University of Melbourne. Sets of sketches of alternative mechanisms with supporting notes and commentary were recorded and provided the experimental evidence for the analysis and interpretation of aspects of designers' performance relevant to this research.

1.2 Aims and Objectives

The research issues and questions to be addressed in this paper are as follows.

Design Rationale and the organisation of experimental information about designer performance in conceptual design. The control of complexity is a recurrent theme in engineering design research [2]. In innovative conceptual design potentially a large number of ideas and strands of argument are capable of being generated. The question then arises on how to handle and organise large quantities of data in terms of an agreed model of the structure of design thinking, i.e. a design rationale – an answer must be sought in the context of this investigation.

Design Focus. Previous unpublished research [3] has shown that when faced with a problem with implicit boundaries not explicitly articulated in the design brief, some designers prefer to narrow their focus by working within self-defined boundaries while others prefer to facilitate ideation by broadening the perceived scope of the problem at hand. In practice either strategy may be appropriate and lead to useful outcomes, no judgement is made here as to the possible superiority of one strategy over the other. However, in the current investigation it would be of interest to note any evidence of narrowing or broadening of design focus.

Feasibility of Design Concepts. In the context of innovative design another question of research interest is this: to what extent do brainstorming and other techniques for stimulating divergent thinking encourage the formation of impractical and/or infeasible design concepts? Perhaps the generation of such concepts is an inevitable result of the conscious effort to suppress premature evaluations, some hard evidence relevant to this aspect of engineering design thinking would be welcome.

Measurement of Design Skills. Shah and co-workers [4,5] have drawn attention to the importance of quantifying design skills according to agreed numerical scales, because of the intrinsic value of such measurements and to meet the demands of funding agencies. For the investigation reported in this paper we wish to know whether such measures are feasible, and if feasible, what are the relevant scales to enable them to be made.

Flexible Thinking – as a component of designer performance. Engineering designers exhibit flexibility in their conceptual thinking when they devise proposals based on a variety of working principles, the more flexible thinkers being those who have recourse to a larger number of working principles. It is intended in this investigation to obtain evidence of ideational flexibility and its relationship to other design skills.

2 THE CASE PROBLEM IN ENGINEERING DESIGN

A summary of the design brief covering relevant aspects of the case problem is included as Appendix A; full details are given in an internal report available from the authors [6]. The design brief was presented to mechanical engineering students in the third year of a four-year programme. All students had previously completed an introductory course on the discipline of engineering design constructed around the text by Samuel and Weir [7]. The students worked to a five week schedule with one design laboratory class per week covering successively problem formulation, conceptual design, detailed design of chosen concept, construction of demonstration model, reporting orally and in writing. In this investigation attention is focussed on the second stage – conceptual design, where at the conclusion of the relevant design class students submitted their "idea logs" in the form of folios of sketches of the mechanisms they proposed. Students were strongly encouraged to generate ideas and proposals in a free flowing manner, postponing evaluations until the next stage of the design process. Up to this point 30 students worked individually on the project; they were designated S1 to S30 to preserve anonymity. The experimental evidence relevant to conceptual engineering design thus consisted of 30 sets of sketches of design concepts together with explanatory notes, all as recorded in the idea logs. Subsequent work done by students to pool these ideas in design teams of three or four is not relevant to the present paper.

The characteristics of the case problem are now summarised in terms of the relevant factors identified in [8], [9] and [10].

Nature of problem: The case problem is clearly in the field of kinematic design: it requires a means of transferring motion from a given input to a given output, in this case as explained in Appendix A from a unison ring capable of small rotations about the longitudinal axis of the compressor to the radial spindles on which a set of stator guide vanes are mounted. We regard kinematic design as an important subsection of engineering design generally: it occupies two chapters in French [11] and continues to be a source of innovative design thinking, see, for example, recent work on constant velocity couplings [12].

Environment in which the case problem is embedded: Manufacturing – Several hundred mechanisms will be required per annum; manufactured in large batches. Operation – The proper functioning of the mechanism is critical to the successful operation of the compressor

Novelty: There are existing precedents to offer the designer guidance. We would describe the case problem as an example of "incremental innovation" as in Marples [13] but the innovation does not have the "step change" quality of those described by Jewkes et al. [14].

3 ANALYTICAL FRAMEWORK

3.1 Design Rationale

Given the availability of designers' sketches and supporting commentary, we need some method of representing their design rationale, i.e. the sequence of ideas and argument leading to the candidate solutions proposed. Representations of design thinking and argument have been devised by several researchers and research groups, notably by Bracewell [15] and Kim et al. [16], and specifically for innovative conceptual design by Marples [13]. Marples found that he could model an innovative design process by a branching tree-like structure (here referred to as a design tree) as a new design evolved through the progressive solution of a series of problems and subproblems. Thus a characteristic of innovative engineering design is that the attempt to solve the initial problem throws up subproblems for which subsolutions have to be generated, and these in turn lead to the next level of problems and possible solutions, and so on until all problems at all levels of the design tree have been solved. A design tree of this hierarchical form has been adopted as the basis for this research. In principle, it is relatively simple to construct, it graphically depicts the flow of deign argument, and the provenance of each strand of argument is displayed.

The analysis of students' responses revealed an intermediate stage in Marples' problem/solution sets which was replicated at successive levels of the design tree, as follows.

(1) recognition of problem or subproblem
(2) generation of some working principle or principles for potential solutions
(3) embodiment of these working principles in engineering hardware.

The recognition of successive subproblems leads to the repetition of this three stage cycle or "triad", and to modelling of the design rationale in terms of sequences of triads.

We provide four examples to illustrate this process, noting that the initial problem at the top of the design tree consists of designing a mechanism to fulfil two kinematic functions – F1 and F2 defined below. The relative position of components is indicated in the schematic diagram Figure 1, where VIGV denotes variable inlet guide vane, and where for each VIGV spindle to rotate by a prescribed amount the functions F1 and F2 must be achieved.

F1: rotate VIGV spindle about its axis, the axis being radial in a plane perpendicular to the horizontal axis of the compressor.

F2: provide motion in the third dimension as the end of the VIGV spindle moves "up" and "down" with respect to a given point on the unison ring.

The reader is referred to Appendix A for further explanation of the terms used here.

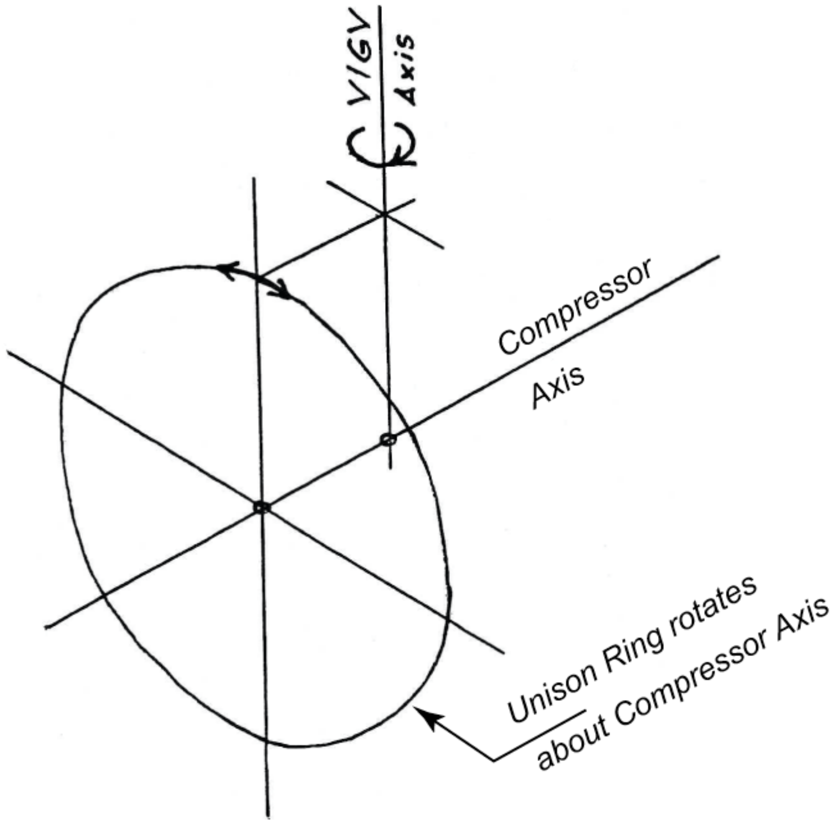


Figure 1. Schematic diagram of motion requirements

Four typical strands of design argument are shown in Table 1 with the following notation.

F1 and F2:	as above.
WP:	working principle for candidate solution.
EMB:	physical embodiment of candidate solution.
SubPr:	subproblem thrown up by a candidate solution.

The reference numbers in parentheses are part of the coding system adopted in the experimental programme [6].

Figure 2 shows the design tree representing the strands of argument in Table 1. Each node corresponds to the completion of one stage of the design argument by a designer. The top node at Level 1 represents the identification of the primary functions F1 and F2, whilst the lowest node in each strand represents the final outcome – usually a sketch of the candidate solution proposed (as in #1, #3 and #4) but occasionally a subproblem still to be dealt with, or just a statement of the working principle capable of solving it (as in #2) but whose physical form has yet to be determined. Figure 3 reproduces copies of the design sketches corresponding to the end points of the four strands of ideation shown in Figure 2.

During the investigation the design tree representing the work of each individual designer was constructed, and the aggregation of all the individual design trees led to the construction of a Master Design Tree encompassing the efforts of all student designers, reproduced here in Appendix B and set out in [6]. The completed MDT comprised 85 strands of design ideas and argumentation.

Table 1. Typical strands of argument in responses to case problem

Level in Design Tree	#1 (Ref. 13.6)	#2 (Ref. 1.4)	#3 (Ref. 3.7)	#4 (Ref. 3.8)
1 – F1, F2	As specified in text of paper	🡐 (ditto)	🡐 (ditto)	🡐 (ditto)
2 – WP	Lever and Pinned Joint	🡐 (ditto)	🡐 (ditto)	🡐 (ditto)
3 – EMB	Lever, Hinge Pin, Fork, separate Components (as existing layout)	🡐 (ditto)	🡐 (ditto)	Hinge Pin integral with Lever
4 – SubPr	Maintaining integrity of assembly	🡐 (ditto)	🡐 (ditto)	Method of assembly
5 – WP	Transverse barrier, fixed in position	Pivoting transverse barrier	Elastic deformation of component	Split surfaces on end of Fork
6 – EMB	Annular ring	Hinged cover plate (sketched)	Clip-on external cover (sketched)	Plane of split perpendicular to VIGV axis
7 – SubPr	Method of assembly	Retention of cover plate	—	Integrity of assembly
8 – WP	Elastic deformation of ring	“padlock system”	—	Retaining cap
9 – EMB	Circlip (sketched)	—	—	Embodiment with retaining screws (sketched)

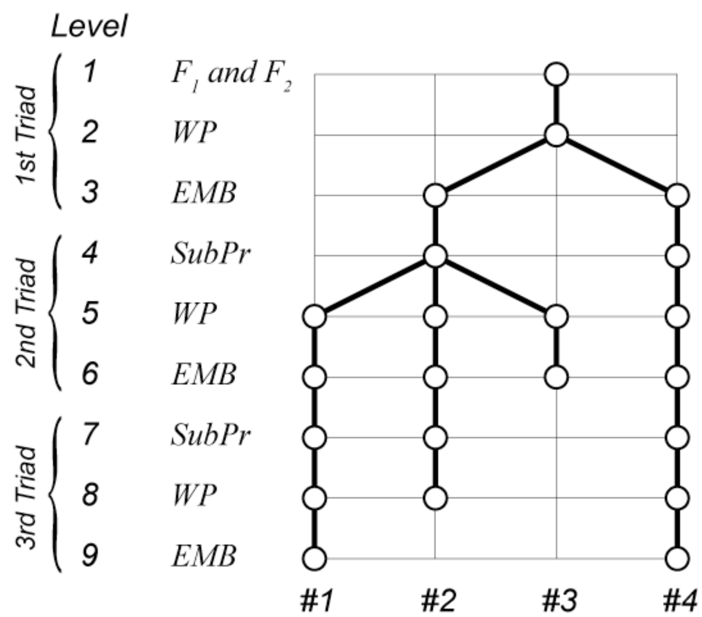


Figure 2. The design tree corresponding to Table 1

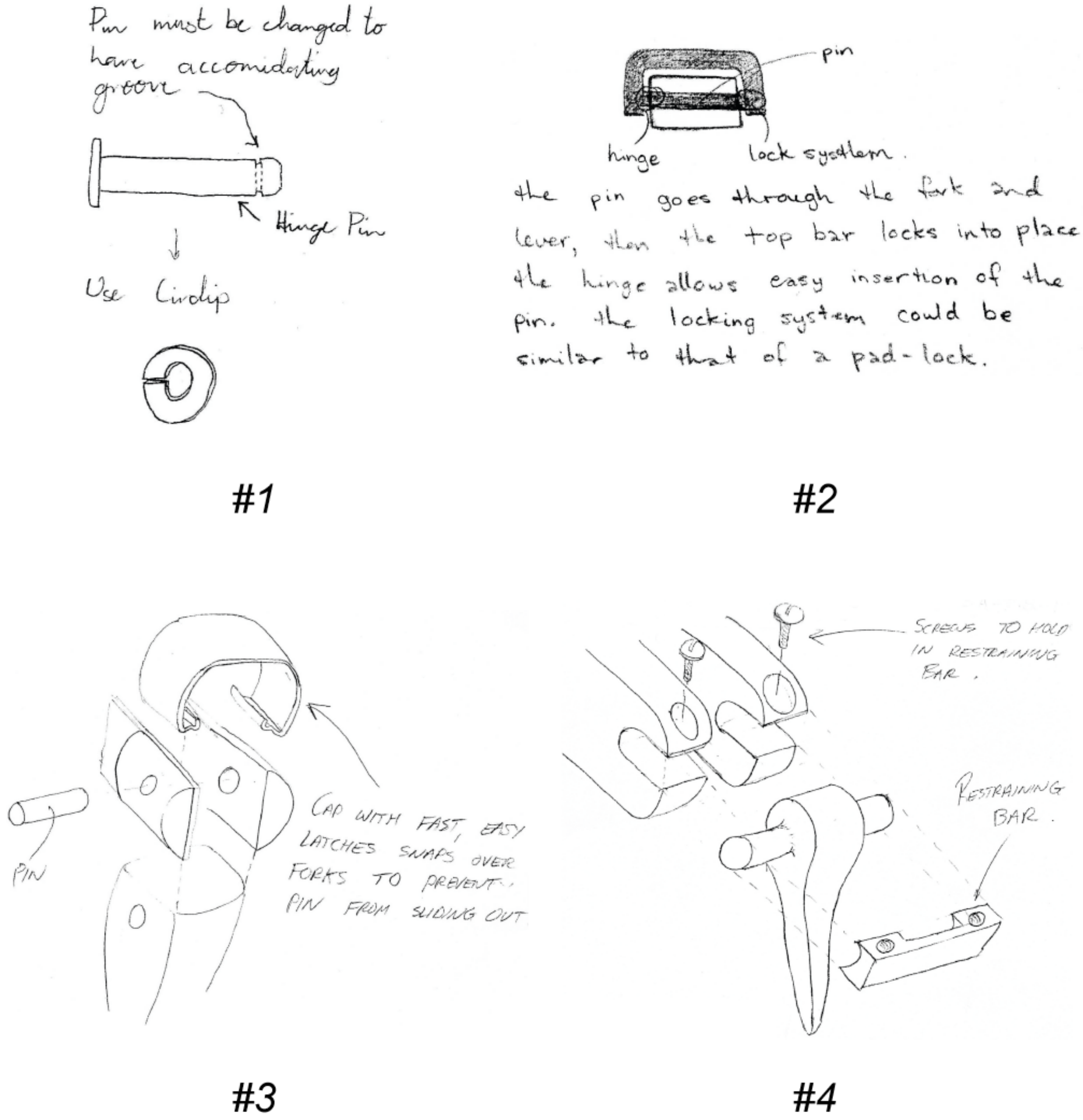


Figure 3. Design sketches corresponding to the end points of the four strands in Figure 1

3.2 Range and Diversity of Design Concepts Proposed

During the construction of the Master Design Tree it was found convenient to sort the great variety of design concepts proposed (the MDT in its final form has 85 strands) into three major categories as follows.

Class I proposals — candidate solutions which treated the case problem as two dimensional, i.e. the need for F2 was ignored. These proposals either derived from the students' inability to visualise the required motions in three dimensions or were the result of a conscious decision to deal with a relatively simple 2D problem first and use this as a launching pad for attack on the full 3D problem. In either case Class I proposals were excluded from the Master Design Tree.

Class II proposals retained the idea of a lever and pin joint, but there were then two possibilities: Class IIA proposals followed the existing design in allowing for a lever, pin joint and fork as three separate components, whereas Class IIB proposals incorporated the hinge pin with the lever as one component (e.g. Strand #4 in Table 1).

Class III comprised more radical proposals in which the unison ring was replaced or extensively modified as the source of the input motion, creating for this purpose some form of circumferential mechanism to impart the prescribed rotary motion to the VIGV spindles.

We note in passing that the design brief did not explicitly differentiate between the problem of designing modifications to an existing compressor and designing a new compressor. A problem had arisen in the operation of a small number of existing compressors, but it was the students' responsibility to define the scope of the exercise on which they were engaged.

3.3 Designer Performance

Design trees facilitate the quantitative evaluation of significant aspects of designer performance, notably (a) flexibility in the creation of different types of design concept, referred to here as ideational flexibility, and (b) the capacity for elaborating on major themes as evidenced by a relatively larger number of final outcomes from a given range of working principles. The amalgamation of high flexibility with a high level of elaboration yields high designer fluency – large numbers of potential solutions. An example will help to make this point clear. An individual design tree (for student S1) is shown in Figure 4. The full lines represent the student's strands of argument while the dotted lines indicate where this student's work fits into the larger design tree, considering only Class IIA proposals as this was the focus of her design investigation.

The following quantitative measures were developed for application in this research.

Ideational flexibility:	The number of categories of design concepts as indicated by the number of nodes encompassed by the designer at any particular level of the design tree: in this case at Level 6 at the completion of the second triad where the opportunity for generating diverse design concepts is the greatest, so the differences between individual designers are more readily measured.
Capacity for elaboration:	The number of design concepts proposed in proportion to the number of nodes encompassed by the designer at the next higher level - generation of working principles (Level 5 in this case) of his or her design tree.

Analysis of the experimental data revealed the latter metric as a relevant performance indicator and a useful means for distinguishing between the efforts of different designers.

As will appear the designer represented by Figure 4 has good ideational flexibility covering six types of design concept at Level 6. Compared to her colleagues, however, her elaboration index at 6 / 4 = 1.5 is about average.

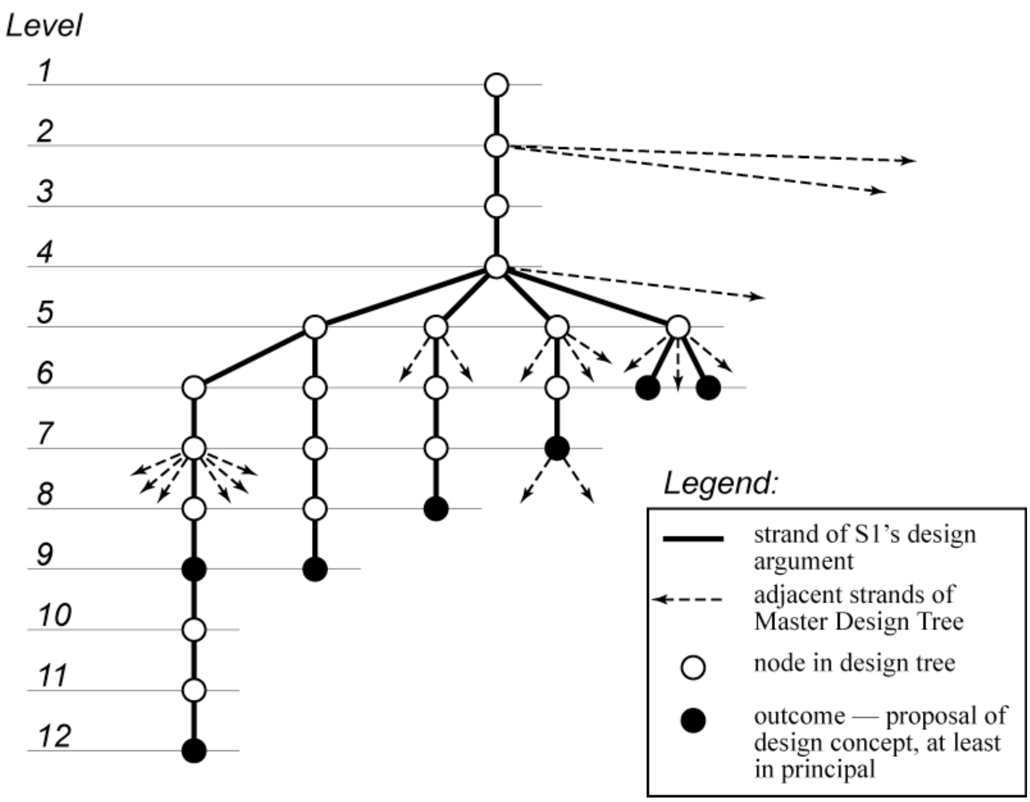


Figure 4. Individual design tree for student S1

4 STUDENTS' RESPONSES TO CASE PROBLEM – RESULTS AND DISCUSSION

4.1 General

Of the thirty students whose responses were initially available for analysis, five returned sketches which dealt exclusively with infeasible motion in two dimensions; another infeasible response comprised unresolved anomalies. In the event the responses of 24 student designers with at least one feasible Class IIA proposal were available for analysis and yielded the results set out below.

Of these 24 students -

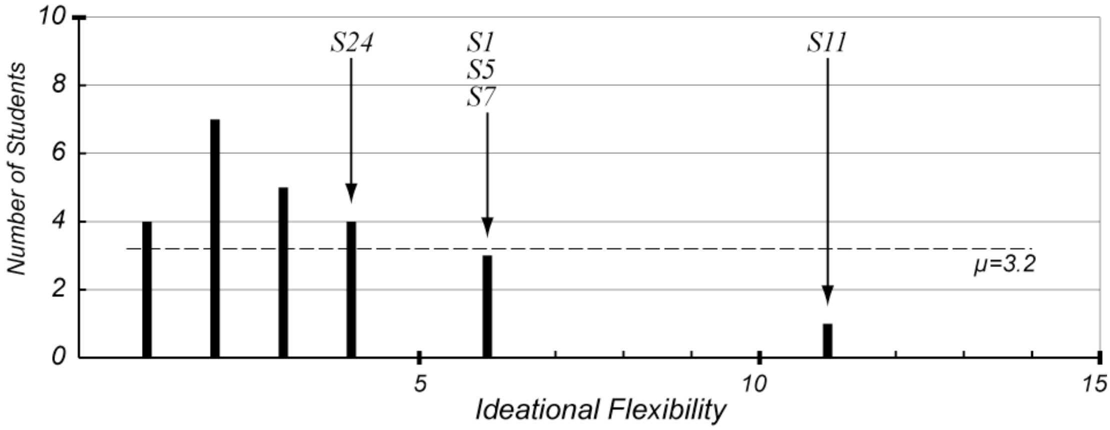
(a) 19 broadened the form of their design investigation to include ideas from one or more of the Classes II B and III, a proportion of 79%; the corresponding proportion recorded in the earlier research was 56% [3]. While this preliminary data is not susceptible to generalisation the authors believe that designers' preference for broader or narrower problem definitions is a significant factor in their performance, and one worthy of further investigation.

(b) 7 included infeasible proposals in their responses. The students generating infeasible responses included S5, S11 and S24, people identified in this research as having a distinctive flair for engineering design, referred to in Section 4.2, below. Furthermore, in that part of this investigation reported in [1] each of the three professionals taking part offered conditionally infeasible proposals in their responses to the design brief.

The activity of engineering design is a complex amalgam of personal creativity and disciplined thinking [17]. The evidence presented here suggests that the discipline may be relaxed during the creative endeavour characteristic of conceptual design.

4.2 Design Skills

The frequency distributions for ratings of ideational flexibility and capacity for elaboration are shown in Figure 5.



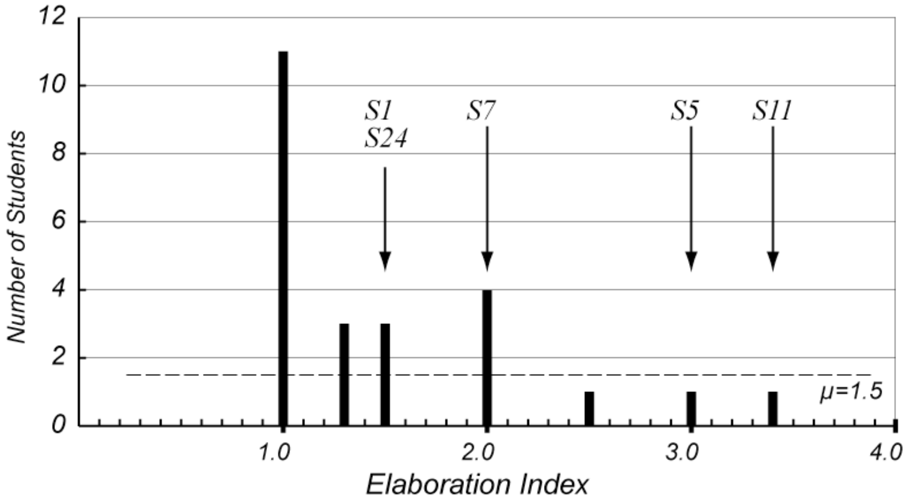


Figure 5. Frequency distributions for ideational flexibility and elaboration index.

Noted on these diagrams are the results of the five students previously identified [1] as having a marked aptitude (or flair) for engineering design due to their superior performance in ideational fluency and sketching ability. The further analysis presented here confirms and adds depth to the earlier finding.

In summary, the significant contributions of flexible thinking and capacity for elaboration to designer performance have been demonstrated.

4.3 Another Matter Related to Designer Performance.

Figure 1 was constructed by one of the authors to illustrate the sorts of motion specified in the design brief. However, it was not part of the original design brief and the symmetry it implies is not an inherent feature of the case problem. In the responses to the case problem only one student designer (S11) considered the possibility of an asymmetric mechanism, i.e. a mechanism not symmetrically oriented with respect to the longitudinal centreline of the lever arm extending from the unison ring to the connection with the spindle axis. In reporting this fact we are led to question why this should be so. Are we as engineers so used to dealing with symmetrical objects (or quasi-symmetrical objects such as the human body) that the idea of symmetry becomes an ingrained part of our thinking? If this is the case then we need to be able to access a strategy or procedure which challenges our habitual modes of thought. One such procedure is the *X / not-X* method mentioned in [18]. In outline this procedure presupposes that for a particular design problem n classes of candidate solutions have been created in which the *i* th candidate ($1 \leq i \leq n$) has attribute *Xi*. Then new candidate solutions are deliberately generated in a boolean *X* and *not-X* way, so that for each *Xi* a *not-Xi* class is created, so leading to a conceptually diverse set of options for the designer to consider. In the case problem under consideration here, given that most designers have generated sets of symmetrical solutions, application of this method would encourage them to devise asymmetrical proposals. Such a procedure or one like it may well part of the intellectual firepower of experienced designers.

5 CONCLUSION

This research has been based on the responses of student designers to a kinematics problem in conceptual engineering design. We review the results in the light of the issues raised in Section 1.2.

(1) Design Rationale. It has been found possible to represent the designers' argumentation by branching hierarchical structures: an individual design tree for each designer and a Master Design Tree encompassing candidate solutions proposed by all the designers. Examples have been given in the paper and in Appendix B.

(2) Design Focus. The majority of the students adopted broader problem boundaries. Of the five students who were later identified as possessing a flair for designing, four adopted a broader approach while one adopted a narrower focus.

(3) Infeasible Proposals. Evidence was presented to show that able designers accepted, at least temporarily, infeasible design concepts during the conceptual phase of engineering design.

(4) Design Skills. The construction of design trees enables the identification and measurement of engineering design skills relating to flexibility of ideation and the capacity to elaborate working principles in different physical embodiments of those principles.

(5) Flair for Engineering Design. The conclusions reached in [1] identifying those students with a distinctive flair for engineering design were confirmed and deepened when the evidence of flexibility of ideation and capacity for elaboration were incorporated into the assessments of designer performance.

(6) Questions for future research. (a) Is there any significance in the observation that most of the better design students adopted broader problem boundaries? (b) Does the exploration of infeasible solutions lead to the identification of diverse, feasible solutions? (c) How does an individual designer generate, or navigate through the Master Design Tree? (d) What attributes (for example, visual skills) limited some students to infeasible two dimensional solutions?

In summary, this investigation has contributed to our understanding of the dynamics of conceptual design in the field of kinematics. The authors' research programme is continuing with further experiments eliciting responses both to the given case problem and to other design problems in the field of energetics. It is intended to report the results at future ICED conferences.

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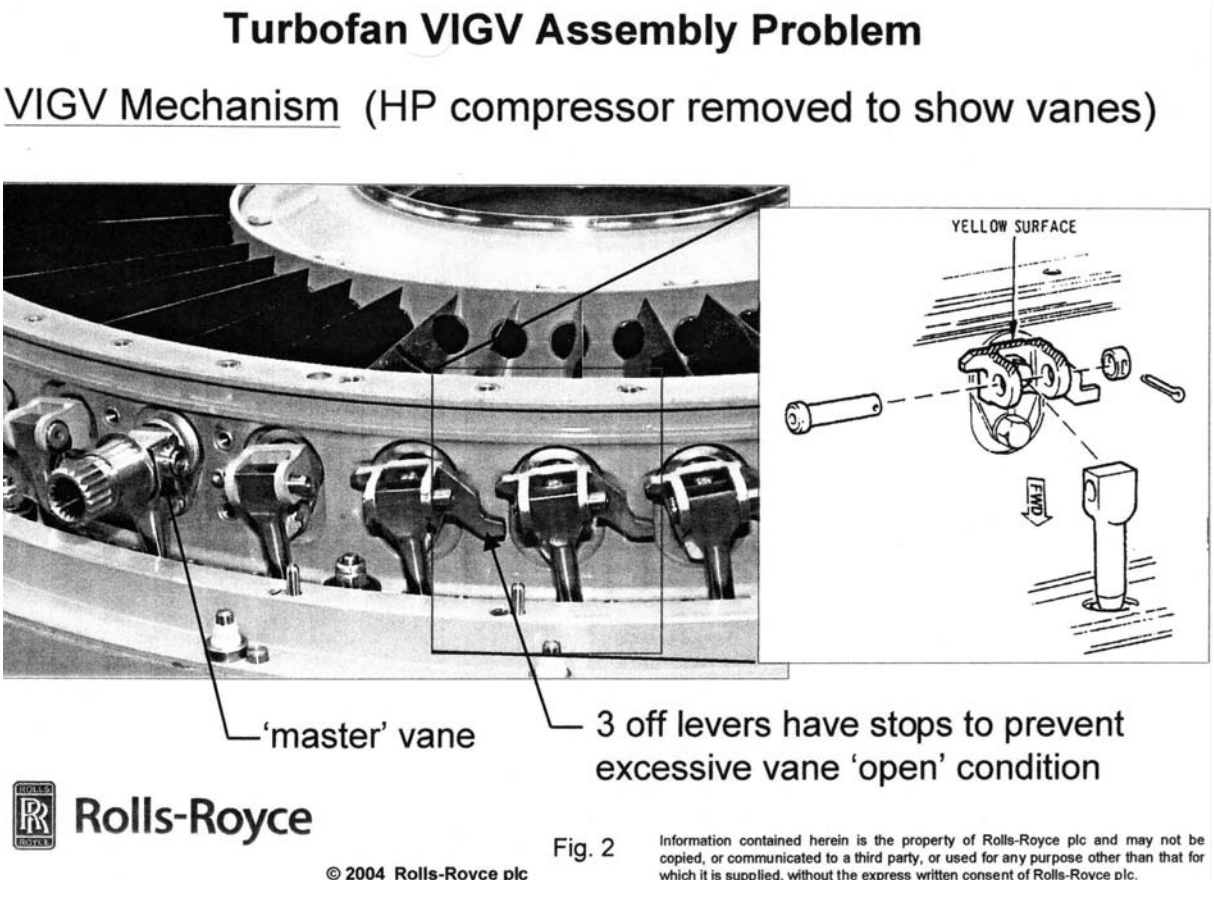
Contact: John Weir
The University of Melbourne
Department of Mechanical Engineering
Australia. 3010
tel: 61 3 8344 6720
fax: 61 3 9596 1105
e-mail: jweir@unimelb.edu.au
web: http://www.mame.mu.oz.au/eng_design/

APPENDIX A — CASE PROBLEM

A potential problem has been identified in relation to the assembly of the variable inlet guide vane (VIGV) mechanism of a medium-sized turbofan jet engine, a two-spool turbofan having two compressors each separately driven by its own turbine. The compressors consist of successive stages of rotor blades and stator vanes. In order to match the orientation of the compressor blade and vane aerofoils to the velocity of the air flowing past them over a wide range of engine speeds, the stator vanes are adjusted relative to the speed and power setting of the engine. The existing mechanism for doing this is illustrated in the diagrams below. The engine under consideration has a single row of 42 variable vanes (VIGV's) at entry to the HP compressor. At the outer end of each of these vanes is a fork, set at a precise angular position relative to the vane aerofoil. An actuating lever is attached to the fork end by means of a hollow hinge pin. This allows the lever to control the angle of the vane, whilst also allowing the lever to pivot in a plane at right angles to that of the vane angular movement. The hinge pin is retained in place by a split pin, which in turn is held in place by having its two legs bent apart. The VIGV levers of all 42 vanes engage in spherical bearings, which are housed in and equally spaced around an actuating ring, also known as a unison ring. The actuating ring is located axially and radially by several small bearings, so that it rotates concentrically with the row of vanes and the engine centreline. The ring is turned through a set angle by a rotary actuator, which drives through a master vane and lever.

As a result of an in-service incident some years ago there appears to be a risk of the split pins not being fitted correctly, due to human error. Although rigorous inspection practices will minimise any risk, design improvements are being sought to completely eliminate the risk. The objective of this exercise is to evolve potential design solutions to the split pin problem and prepare a report for company management. During the conceptual phase of the design it is essential that you keep an Idea Log of your design thinking, and fill it with hand sketches and brief notes. Further information is available from the Engineering Design web site.



APPENDIX B — MASTER DESIGN TREE