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A CASE STUDY TO ILLUMINATE THE CONCEPTS OF DESIGN EXPERTISE AND DESIGNER FLAIR IN ENGINEERING DESIGN

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Keywords: conceptual engineering design, designer performance, sketching ability.

1 Introduction

1.1 Background

The paper addresses the issue of design expertise and designer flair in the context of the conceptual phase of the engineering design process as it is here that key design skills in idea generation and disciplined creativity are displayed. The investigation to be reported in this paper is based on a problem which frequently arises in the design of axial flow turbomachinery where rotating arrays of blades impart energy to a stream of fluid in 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, this to 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 (a) undergraduate students of engineering design at the University of Melbourne, and in a follow up study to (b) three mechanical engineers with extensive experience in engineering design. Sets of sketches of alternative mechanisms – ideas generated by both student and experienced designers – were recorded and provided the experimental evidence for the analysis and interpretation of the designers' performance.

1.2 The role of sketching in conceptual engineering design

Sketching enables the designer to bridge the knowledge gap between abstract statements of objectives and requirements on the one hand and the physical object to be designed on the other [1, 2]. Sketches provide the designer with the facility to develop and test the physical forms of candidate designs, the medium for an internal dialogue or reflective conversation by which the designer extends and deepens his/her understanding of the problem being addressed [3]. New constraints may be revealed or new functions identified – new in that they are additional to the knowledge contained in the original brief presented to the designer. In engineering terms we are concerned with the designer's "thinking sketch" [4, 5] which supports simulations of the artefact being designed and its properties. The preceding discussion suggests that sketching ability contributes to the designer's intellectual weaponry as it facilitates graphic visualisation and mental simulation of the properties of candidate designs. We would hypothesise that sketching ability (and associated skill in graphic visualisation) is an important component of expertise in engineering design in that possession of this skill enables the designer to engage in a dialogue with him/herself, and, in the case of the expert designer, help to uncover the critical "first principles" identified by Cross [6] This is not to preclude the possibility of some expert designers making little use of sketches or drawings to advance their thinking as they have developed effective means of using mental imagery to the same end, a possibility canvassed in [3]. An instance of an expert engineering designer postponing sketching until his thinking was comparatively well advanced and key issues identified was encountered in the research reported in [7].

Working in the field of architectural design, Goldschmidt [2] discussed the possibility of a designer developing a "personal shorthand", a concise graphical language which enables him/her to quickly set down the leading features of candidate design concepts in an endeavour to ensure the visual record matches the rapidity with which ideas are generated in the human brain. An example of the development and application of such a graphical shorthand in engineering design was noted in [7]. In a different field, Hamilton [8] describes how the notebooks of the philosopher Ludwig Wittgenstein are "interlaced with thinking sketches", models for visualisation of the relations between the subjects of his speculations.

1.3 Aims

We are concerned with the performance of designers attempting to solve a novel problem (novel to them) in engineering design when they have reached the conceptual stage of the design process and are generating candidate proposals. The questions to be addressed include the following. (a) What are the characteristics of designer performance, the features which distinguish the work of one engineering designer from another? (b) Does superior performance correlate with sketching ability? (c) Do some designers make use of their own graphical language, a personal shorthand? (d) Is there evidence for the adoption of strategies of ideation previously reported in the research literature on engineering design?

In the context of these questions and the matters raised by them, the specific aims for this investigation were formulated as follows.

(1) To determine the distinctive features of the responses of student designers and professionals to the case problem in conceptual engineering design.

(2) To investigate the relationship between designers' performance established in (a) and their sketching ability displayed in representing candidate design concepts.

(3) To record any evidence obtained regarding (i) design thinking strategies, and (ii) the creation and use of a graphical shorthand, to comment on and interpret this evidence in the light of previous research.

(4) To review the experimental results for evidence of superior performance on the part of individual designers, the display by them of a distinctive flair for engineering design.

Note: The work of the student designers is reported first and analysed in depth. The responses of the professionals to the case problem will be reported only in so far as they differ from the students or throw additional light on the research questions posed earlier in this section.

2 The case problem in engineering design

2.1 Administration

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 [9]. The design brief was presented to mechanical engineering students in the third year of a four-year programme and separately to three experienced professionals. All students had previously completed an introductory course on the discipline of engineering design constructed around the text by Samuel and Weir [10]. 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 are designate S1 to S30 to preserve anonymity. Subsequently, they formed teams of three or four: the members of each team pooled their ideas, hopefully to produce an optimum team effort. The experimental evidence relevant to conceptual engineering design thus consisted of 30 sets of sketches and drawings of design concepts as recorded in the idea logs.

Each of the three professionals, designated here as P1, P2 and P3, had had 10 to 15 years experience at responsible levels in their fields.

P1 — Innovative product design and development and related R & D, has eight patents.

P2 — Design of capital equipment, has dealt with major environmental and safety issues, known as thoughtful designer and abstract thinker.

P3 — Evolutionary design, extrapolation from existing artefacts, good analyst.

The professionals, working in their own time, were asked to respond to the design brief by generating and sketching design concepts, keeping records of the approaches they adopted.

2.2 Characteristics of case problem

Methods of classifying problems in engineering design have been proposed by a number of workers, e.g. Ullman [11] and Samuel and Weir [12] at a general level, and Griffin [13] in relation to product development. The characteristics of the case problem are now specified in terms of relevant factors extracted from these references.

Nature of problem: Kinematic design, motion transfer in which the input motion and the required output motion are specified.

Environment in which the case problem is embedded: *Manufacturing* — Several hundred mechanisms will be required per annum; they will be manufactured in large batches; *Operation* — The proper functioning of the mechanism is critical to the successful operation of me compressor of which it is a part; any failure would have serious consequences.

Complexity (cognitive load on the designer): Rated low, one current design has five components as shown in Appendix A.

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 [14] but the innovation does not have the "step change" quality of those described by Jewkes et al. [15].

3. Students' responses to case problem

3.1 Analytical framework

The experimental evidence of students' responses to the case problem consisted of 154 A4 pages of sketches and explanatory notes from 29 students. The nine pages of work from one student who used CAD drawings to illustrate his ideas instead of the requested freehand sketches are excluded from the results and analyses. The responses were very diverse; a selection of the students' sketches is included in Appendix B to indicate this diversity. The examples in Appendix B cover the following.

(1) Ref. no. 13.6 (S26) Replacement of split pin by circlip.
(2) Ref. no. 13.9 (S26) Rigid lever plus slot to accommodate relative motion.
(3) Ref. no. 3.9 (S6) Proposal based on the notion of positional locking.
(4) Ref. no. 1.4 (S1) Pivoted retaining clip (poor sketch but good idea).
(5) Ref. no. 3.7 (S5) Flexible components to maintain integrity of assembly.
(6) Ref. no. 7.2 (S12) Redesign to make hinge pin integral with lever arm.
(7) Ref. no. 13.2 (S24) One page from a personal brainstorming session (3 pages in all)

The onus is on any designer faced with the case problem to act creatively and come up with a set of proposals of a greater or lesser degree of novelty. Psychological research on creative behaviour has identified three dimensions of creative performance, namely — ideational fluency (the number of ideas generated); ideational flexibility (the number of categories into which these ideas fall); originality (the existence of ideas unique to the person proposing them). Engineering designers are disciplined thinkers whose work must always conform to the requirements of scientific validity and economic worth. The applicability of these dimensions to the "disciplined creativity" [16] of engineering design is, at least to some extent, an open question. We will proceed on the basis that they are appropriate to this investigation and then assess the results obtained. The 154 pages of students' work is also analysed for evidence of other relevant aspects of designer performance, namely — the capacity displayed in their sketches for visualisation of objects and motions in three dimensions; the sketching ability displayed and its relation, if any, to ideational fluency (ratings of sketching ability scored out of 10, the average of two independent assessments by authors WPL, JGW); and finally, strategies for generation and development of proposals.

3.2 Features of responses of student designers

Features of the responses of the students to the case problem relevant to their performance as designers are set out below. These observations are analysed and discussed in Section 3.3.

Creative effort:
Ideational fluency ranged from 2 to 21, mean value = 6.2, see Figure 1. Ideational flexibility ranged from 1 to 6, mean value = 2.6. With respect to originality, 11 students came up with unique ideas not duplicated by their colleagues.

Visualisation, sketching:
22 students sketched their ideas in oblique or isometric projection. The sketches of the other seven students were two-dimensional. Five of the seven considered the required motion transfer to be two-dimensional and appeared to be locked into a 2D mode of thinking. Sketching ability varied widely, ratings ranged from 2/10 to 10/10, mean value = 6.1. Figure 2 shows the plot of ideational fluency against rated sketching ability for the 29 student designers.

Correlations:
The product moment correlation coefficient for ideational fluency (IF) versus sketching ability (SA) for the results shown in Figure 2 is 0.33, statistically significant at the 8% level. If the outlier corresponding to SF = 14, SA = 4 is removed (student S24, see discussion in next Section), then the coefficient rises to 0.39, significant at the 5% level. There is a significant positive correlation between ideational fluency and flexibility.

Strategies observed:

- When compiling their idea logs, 11 students included some form of initial review of the data available to them, although not asked to do this. This usually took the form of an annotated sketch of the existing design. However, a detailed analysis, not included here for reasons of space, showed that the students' subsequent performance in conceptual design did not depend on whether or not they prepared an initial review.
- One student engaged in a personal brainstorming session, item (7) in Appendix B is an extract of his work. In this case the student's sketches are crude, almost a form of graphical shorthand, as he strived to get pictorial representations down on paper at a speed consonant with the rate at which his brain was working.
- Three students developed their ideas by first sketching mechanisms to transfer motion in two dimensions and then moving onto motion transfer in three dimensions, item (2) in Appendix B is an example of this.
- A few students transformed an existing design concept relying on the application of a certain working principle to a new concept relying on another related but different working principle, in one case moving from a design based on the elastic behaviour of a component to one based on plastic deformation.

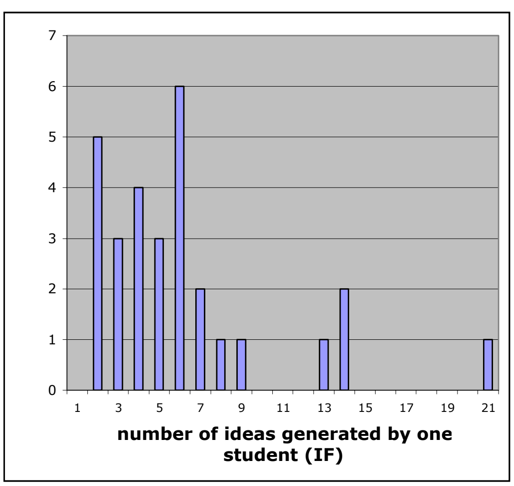

Figure 1. Frequency plot for ideational fluency.

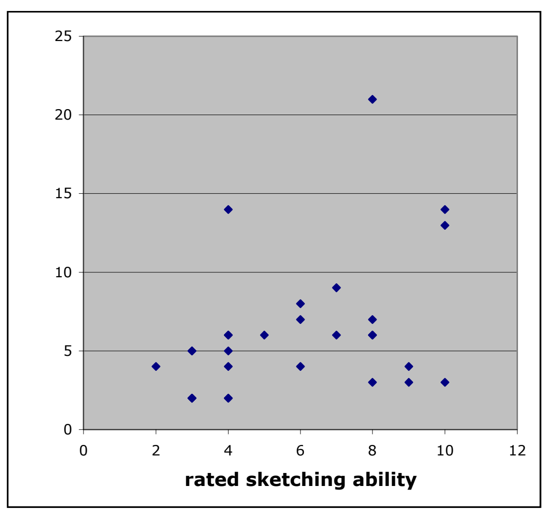

Figure 2. Relation between ideational fluency and rated sketching ability.

3.3 Discussion

Creative effort: There are very wide variations in ideational fluency, flexibility and sketching ability, with the highest scores being between five and ten times the lowest. Since all the students are carefully selected entrants to the university of above average mathematical and scientific intelligence, we are led to suggest that their creative performance in engineering design represents another dimension of intelligence, a hypothesis consistent with previous research findings [17]. Ideational fluency was strongly correlated with flexibility, the great majority of students performing similarly on these dimensions. However, there were a few notable exceptions where the designers scored significantly higher on ideational fluency because of their superior ability to perceive associations and linkages, and this enabled them in effect to create many more variations on a theme than their peers (student S15 is an example, see Table 1). The fact that 11 students (38% of the total of 29) came up with unique design concepts supports the view that creative individuals working on their own may be a more valuable source of ideas than teams, at any rate in the early stages of an innovative project, as they are not restricted by "groupthink", the tendency for members of teams to conform to the prevailing mind set [18].

Visualisation, sketching: Gardner [19] has argued persuasively for recognition of the multiple facets of human intelligence, spatial ability being one of his seven categories of intelligence, and it should be noted that the five students revealed to have a low capacity for spatial visualisation have demonstrated high intelligence in other parts of their studies in mathematics and science. In Section 1.2 we set out the argument for predicting a positive relationship between sketching ability and ideational fluency. The positive correlation observed in this research provides evidence in support of this prediction. This is not to deny that individual designers may sacrifice quality of sketching to enable their visual records to keep pace with a high mental output of ideas - student S24 is an example of this. In the context of this investigation (kinematic design in three dimensions) sketching ability is seen as an aid to design thinking, but this is not to preclude the existence of exceptional thinkers who rely more on internal representations rather than external aids.

Strategies: We recapitulate the strategies adopted by students when attacking the case problem in conceptual engineering design, as follows.

(i) Execution of an initial review.
(ii) Personal brainstorming, supported by a succinct graphical shorthand to facilitate rapid recording of design concepts as they are visualised.
(iii) Simplification of the given problem followed by progressive generalisation until all design requirements are satisfied, a process we describe as conceptual hill climbing.
(iv) Forming conceptual associations, linking together related working principles or embodiments of these working principles.

These observations largely parallel those reported in [7] although the evidence from the current investigation is sparse because only a few students provided written explanations in their idea logs to enable their ideational strategies to be identified with confidence. Where we have been able to identify the students' strategies we find that they fall into the four noted categories (i) to (iv) and that these categories correspond to those found in previous research. Furthermore, later in Section 4 examples of these four strategies are found in the responses of the professionals to the case problem.

Superior Performance – Designer Flair: This investigation has focussed on creation of design concepts, and as pointed out in Section 2.1 students were encouraged to propose design concepts in a free-flowing manner with evaluations postponed until a later stage of the design process. For this reason and because apparently infeasible ideas can inspire new, valuable trains of thought no formal assessments of quality of proposals were made. However, for students to qualify for entry into a Table of superior performers, they had to have proposed at least one design concept assessed by an independent reviewer to be of sufficient quality to be worthy of detailed follow-up in practice. In addition they had all to have come up with at least one unique idea different from anything proposed by their peers. Of the student designers taking part in this investigation, three exhibited superior performance across the dimensions of designer performance considered here to be relevant to successful conceptual engineering design, as shown in Table 1. In the context of the case problem each of these persons has displayed a flair for innovative mechanical design.

Table 1. Superior performance in conceptual engineering design.

Student	Ideational characteristic		Sketching ability
	Fluency (no.of ideas)	Flexibility (no. of classes)	(rating out of 10)
Mean value:	*6.2*	*2.6*	*6.1*
S5	14	4	10
S7	9	5	8
S11	21	6	8
S1	7	6	5
S24	14	5	4

The responses of two other students fulfilled all but one of the criteria for designer flair and are worthy of note despite the relatively poor quality of their sketches. Their performances are summarised in the bottom two lines of Table 1. The performance of student S1 is distinctive in the high level of flexibility displayed, and it might well be that her marked capacity for flexible thinking would enable her to contribute valuable ideas to other innovative design projects. Student S24 deliberately sacrificed quality of sketching and developed a form of graphical shorthand, in a personal brainstorming session.

4. Responses of professionals to the case problem

To convey the flavour of the professionals' responses to the case problem examples of their work (photo-reduced) are attached in Appendix C: one page of sketches from professional P1, one page of design diagrams from professional P2, a line diagram depicting the required motion transfer from P3. The significance of the work of P1 and P3 is clear; we interpret P2's diagrammatic sketches as part of his attempt to develop a graphical shorthand representing design concepts he has generated. As might perhaps be expected from his brief c.v. given in Section 2.1, P1 was the most fluent thinker of the three: his sketches of 18 possible design concepts covered 4 pages. The professionals were volunteers who worked in their own time at their own pace. In the event each had only a limited time to devote to this exercise so that their responses can only be regarded as indicative rather than the result of participation in a controlled laboratory experiment. Nevertheless, when compared to the students' output their idea logs exhibited some significant features, particularly with respect to the problem solving strategies adopted and the level of abstraction at which the case problem was viewed.

Each professional conducted an *initial review*, as follows: P1 – sketch of existing design plus clear realisation (described in follow-up interview) of the three dimensional nature of the motion to be transferred; P2, P3 – sketches in the form of line diagrams depicting the essentials of the motion to be transferred plus calculations of the distances involved (P3's sketch is shown in Appendix C). The purpose of the initial review is to clarify the nature of the "givens" in the design brief and to make explicit any dimensional constraints on the mechanism to be designed. It is of interest to note that no student sketched an abstract representation of the type prepared by P2 and P3. P1 has an extremely high capacity for visualising in three dimensions (has scored 25 out of 25 on the Mental Cutting Test), and did not need this aid. The reason for the students' inability or unwillingness to formulate the geometrical essentials of the case problem in this way is not clear, and will be the subject of further research. As illustrated by the excerpt of his work exhibited in Appendix C, P2 went a long way towards developing a *graphical shorthand*. There was no evidence of a *conceptual hill climbing* strategy in P1's response, but P2 and P3 started by sketching proposals for transferring a simplified 2D motion and then moved on to more general proposals for 3D motion transfer; they adopted the same conceptual hill climbing strategy for attacking the case problem. *Conceptual associations* were evident in P1's response but not in those of P2 and P3. P1's extensive experience in automotive and agricultural machinery provided him with a rich repertoire of artefacts and devices on which to draw. In a follow-up interview P1 mentioned the following: I.C. engine crankshaft; sheep shearing handpieces; king pin; steering knuckle; Scotch key; door latch; retractable ball point pens. Perhaps one could generalise and argue that engineering designers with a flair for their professional work have learnt to continually interact with their physical environment in a constructive manner to create an ever-expanding resource of artefacts and devices on which they can draw as desired.

5. Review

In the context of this investigation and the case problem on which it is based we are now in a position to answer the questions posed in Section 1.3.

Characteristics of superior designer performance — designer flair
Five criteria were proposed in Section 3.3 for distinguishing superior designer performance in the case problem, namely, (a) high ideational fluency, (b) high ideational flexibility, (c) good sketching ability, plus (d) originality and (e) quality of ideas, both formulated as hurdle requirements. Three students (10% of the group) performed well on all criteria, and have displayed distinctive designer flair. Two other students performed well on all criteria except (c), and would be expected to be capable of making valuable contributions to future projects in innovative engineering design.

Designer performance and sketching ability
Designer performance and sketching ability were found to be positively correlated, although the relationship was partially obscured by the action of a few designers who drew very diagrammatic sketches, presumably to facilitate rapid visualisation. Superior performance is assisted by good sketches but sketching ability does not appear to be a necessary component of such performance : one student designer (S1) displayed a high level of flexibility in her thinking but her sketches did not rate highly.

Engineering designers and graphical shorthand
Despite the argument in favour of the development of a graphical shorthand design language (see Section 1.2), only two designers were observed to do this in this investigation - student S24 and professional P2. While the development of such a language appears to be an

intensely personal matter, the experimental evidence presented here confirms the speculation that some designers adopt this strategy to aid their conceptual thinking.

Ideational strategies in conceptual engineering design

The evidence obtained in this investigation concerning ideational strategies has been shown to be consistent with the results of previous research and to that extent confirms the earlier results. But the evidence is limited, and further research is required with other case problems in innovative mechanical design to underpin the basis of the conclusions reached.

6. Conclusion

This paper has presented and discussed the responses of engineering designers to a case problem in innovative mechanical design. In conclusion we draw attention to significant aspects of the research and their implications for the practice of engineering design and for the education of engineering designers.

1. Characteristic features of the performance of engineering designers in the conceptual phase of the design process have been identified and instantiated in a quantitative way.

2. Some designers (between 10% and 20% of the highly intelligent group taking part in the investigation) have displayed superior performance and this has been characterised as designer flair.

3. The hypothesised positive relationship between designer performance and sketching ability has been confirmed, subject to the existence of moderating influences notably the need for designers to get ideas down on paper rapidly.

4. The fact that a minority of those taking part in the investigation displayed a distinctive designer flair is relevant to the recruitment and selection of engineering designers for work on innovative projects.

5. The evidence adduced for the adoption of particular ideational strategies — graphical shorthand, conceptual hill climbing, conceptual associations — while limited in extent, is in line with previous findings, and supports the validity of these findings.

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References

1. Goldschmidt, G., “On visual design thinking: the vis kids of architecture”. *Design Studies,* 15,1994, pp. 158-174.

2. Purcell, A.T. and Gero, J.S., “Drawings and the design process”. *Design Studies,* 19, 1998,pp.389-430.

3. Suwa, M. and Tversky, B., "What do architects and students perceive in their design sketches? A protocol analysis". *Design Studies,* 18, 1997, pp.385-403.

4. Ferguson, E.S., *Engineering and The Mind's Eye,* M.I.T. Press, Cambridge, Mass., 1992.

5. McGown, A., Green, G. and Rodgers, P.A., "Visible ideas ; information patterns of conceptual sketch activity". *Design Studies,* 19,1998, pp.431-453.

6. Cross, N., "Creative cognition in design processes of exceptional designers", in T. Hewett and T. Kavanagh (eds.). *Creativity and Cognition,* ACM Press, New York, 2002.

7. Lewis, W.P., Weir, J.G. and Field, B.W., "Strategies for solving complex problems in engineering design", *Proc. ICED 01,* Glasgow, 2001, pp. 109-114.

8. Hamilton, K., "Wittgenstein and the mind's eye", in J.C. Klagge (ed.), *Wittgenstein: Biography and Philosophy,* Cambridge University Press, Cambridge, 2001, pp.66-67.

9. Lewis, W.P., "Aspects of Engineering Design Thinking: an Innovative Mechanism", Research Note 03/04, Mechanical Engineering, University of Melbourne, 2004.

10. Samuel, A.E. and Weir, J.G., *Introduction to Engineering Design: Modelling, Synthesis and Problem Solving Strategies,* Butterworth-Heinemann, Oxford, 1999.

11. Ullman, D.G., "A taxonomy for mechanical design". *Research in Engineering Design,* 3,1992,pp.l79-189.

12. Samuel, A.E. and Weir, J.G., "A parametric approach to problem enformulation in mechanical design", *Proc. ICED 97,* Tampere, pp. 3/83 to 3/90.

13. Griffin, A., "Metrics for measuring product development cycle time". *Journal of Product Innovation Management,* 10, 1993, pp. 112-125.

14. Marples, D.L., "The decisions of engineering design", *I.E.E.E. Transactions on Engineering Management,* EM-8, 1967, pp. 55-71.

15. Jewkes, J., Sawers, D. and Stillerman, R., *The Sources of Invention* (2nd edition), Macmillan, London, 1969.

16. Bailey, R.L., *Disciplined Creativity for Engineers,* Ann Arbor Science Publishers, Ann Arbor, Mich., 1978.

17. Lewis, W.P., "Creativity in engineering design". *Bulletin of Mechanical Engineering Education,* 7, 1968, pp. 193-211.

18. Robbins, R. and Finley, M., *Why teams Fail,* Orion Publishing, London, 1998.

19. Gardner, H., *Frames of Mind: the Theory of Multiple Intelligences,* Basic Books, New York,1993.

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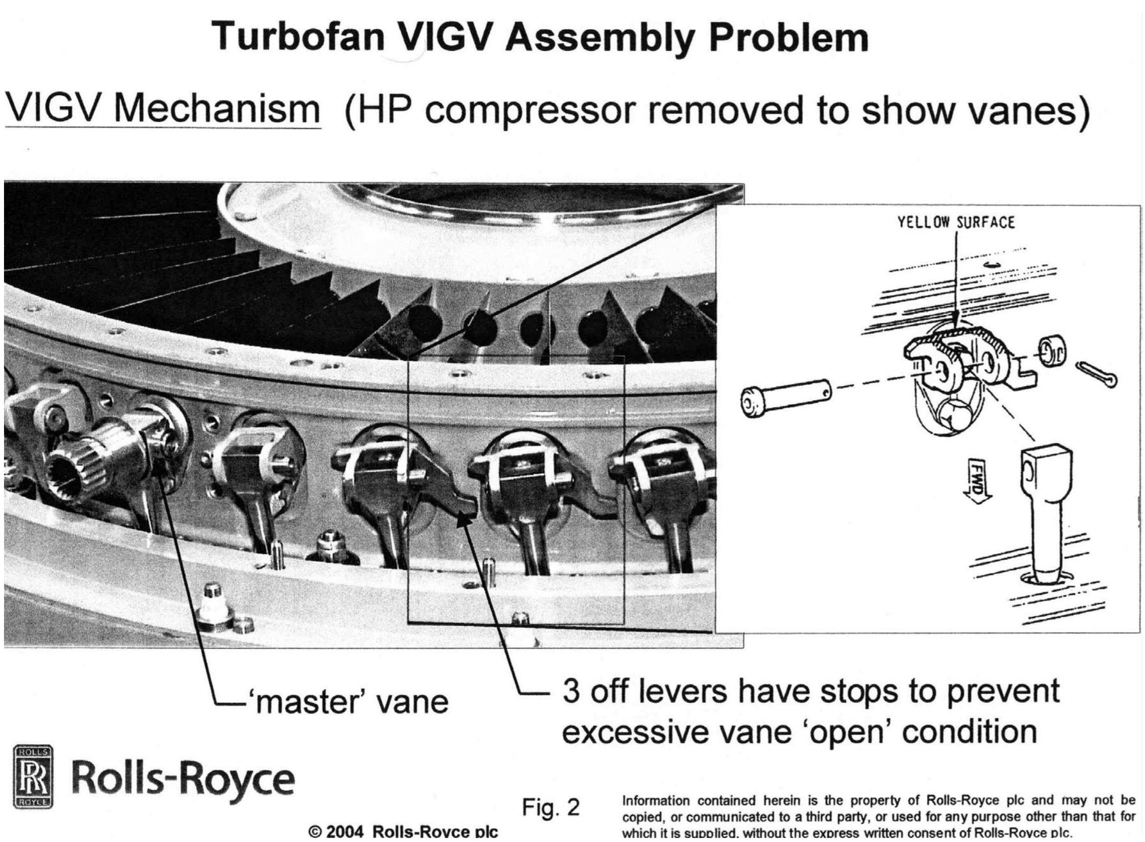
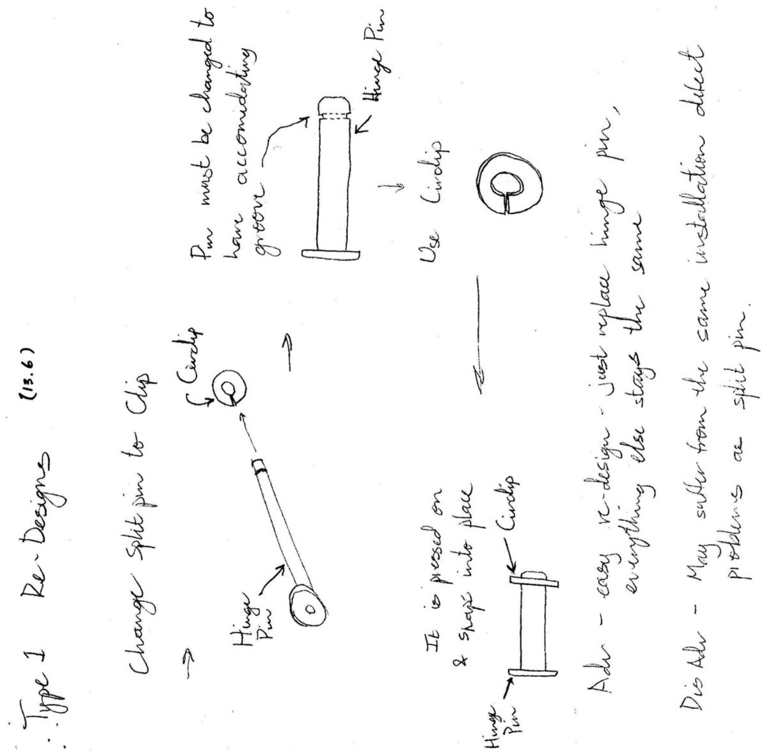
APPENDIX A — OUTLINE OF DESIGN BRIEF FOR CASE PROBLEM

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 — EXAMPLES OF STUDENTS' RESPONSES TO CASE PROBLEM



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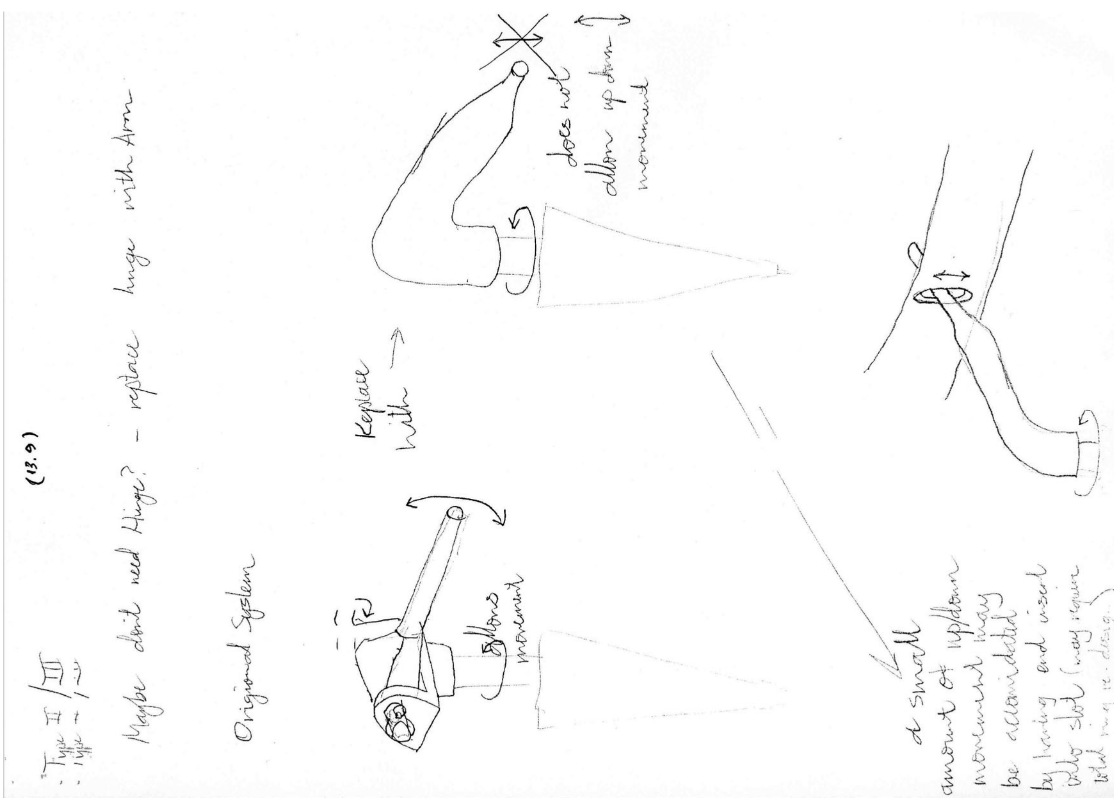

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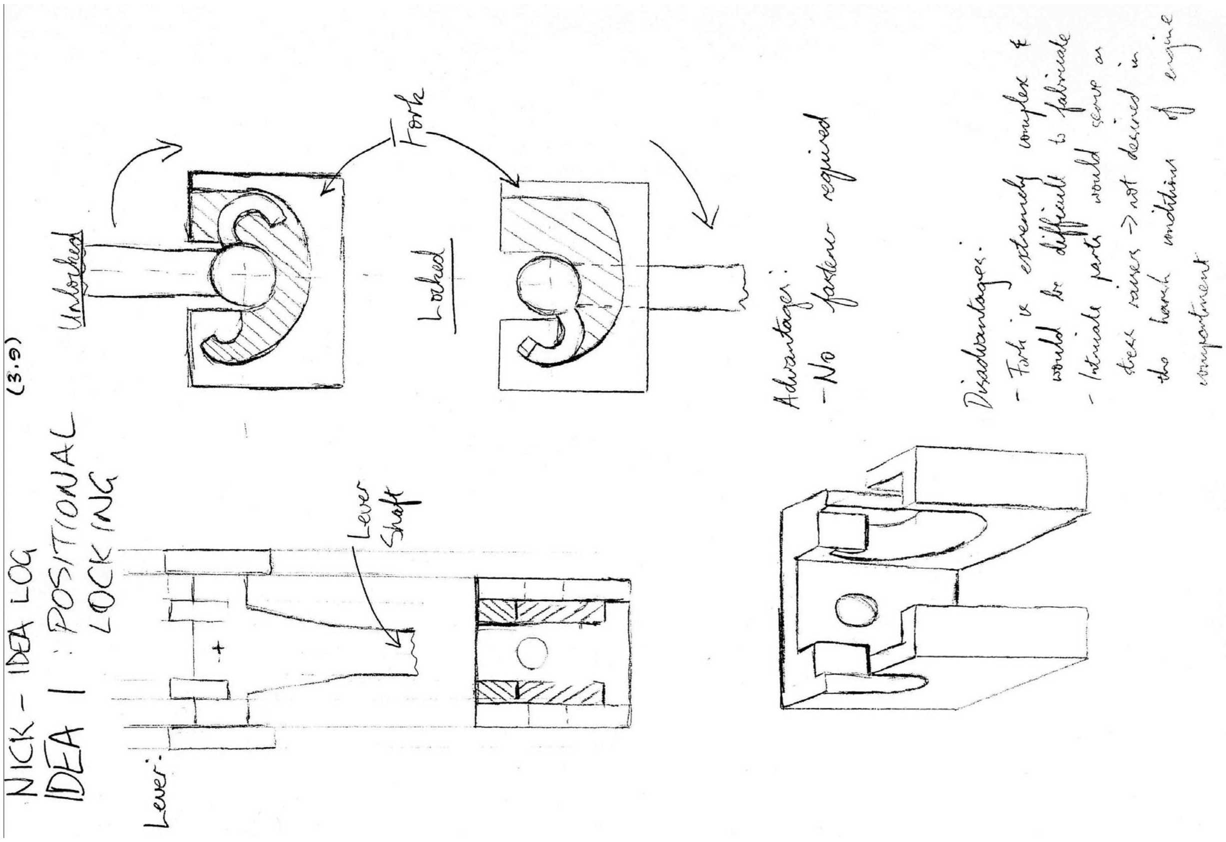

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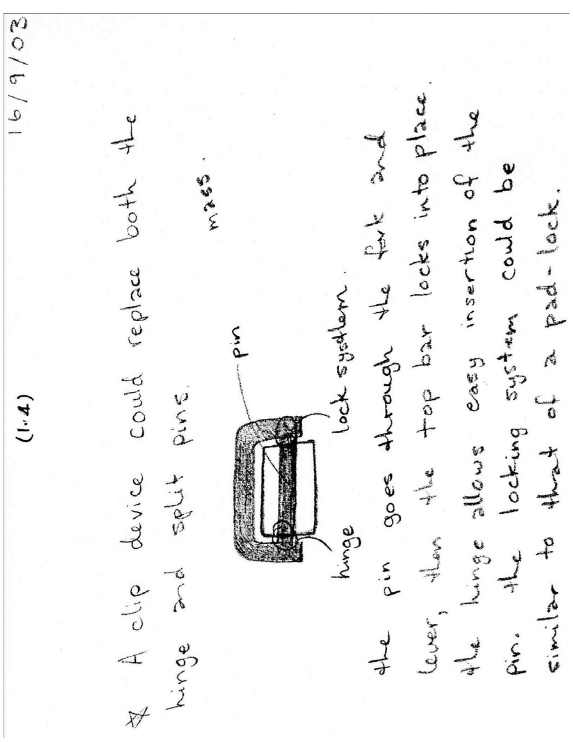

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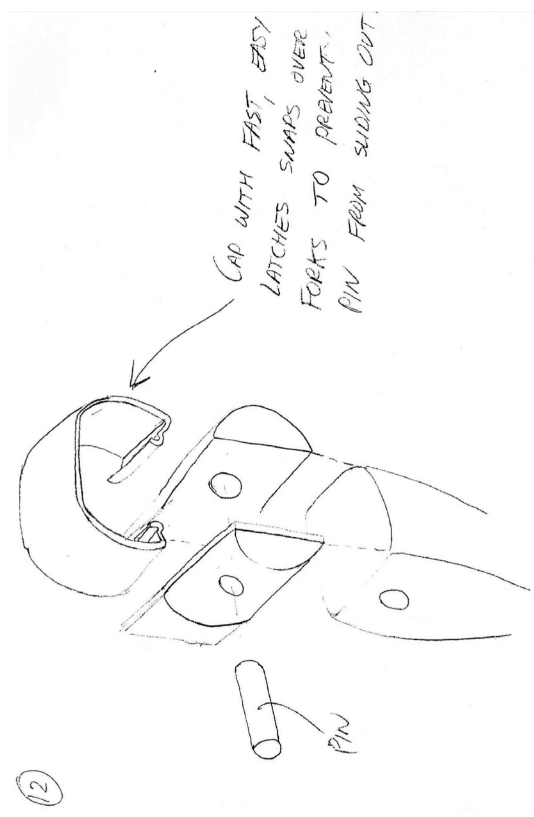

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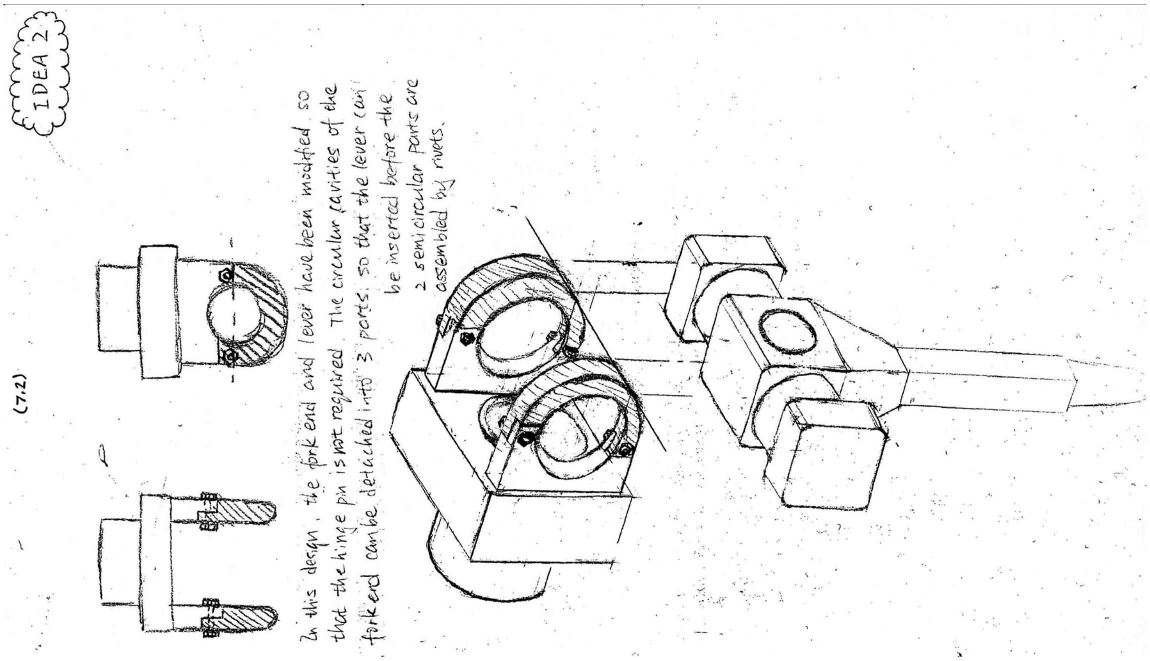
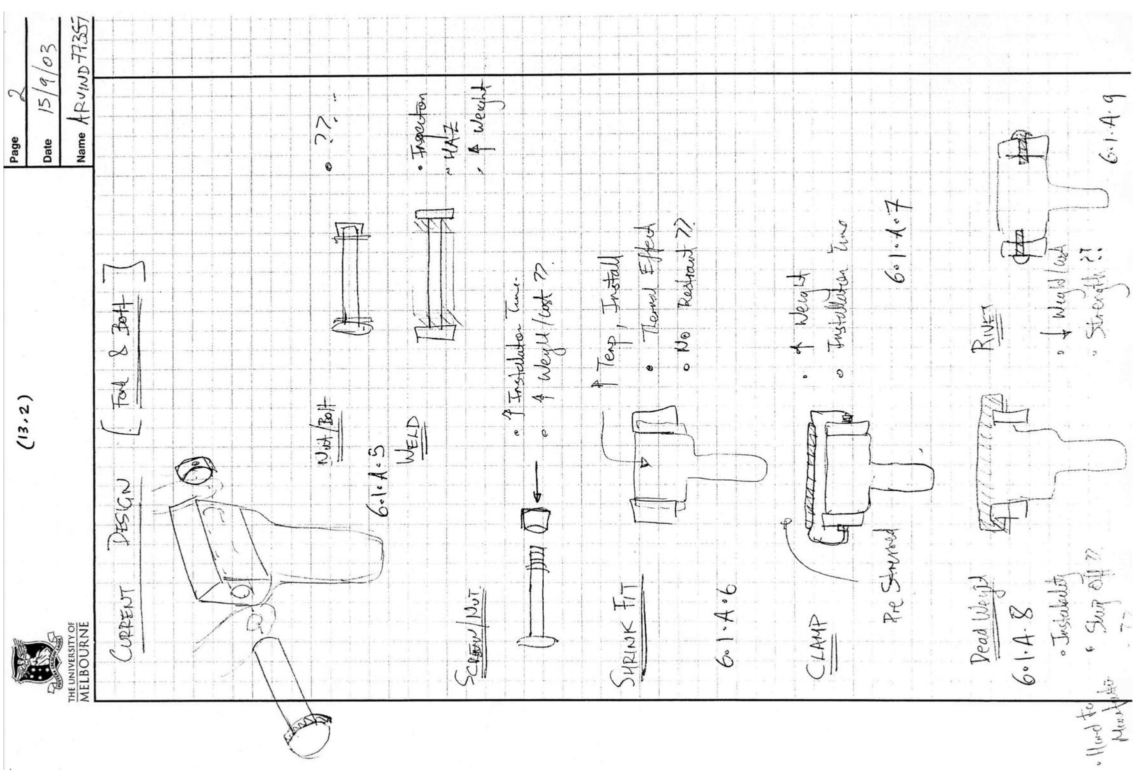


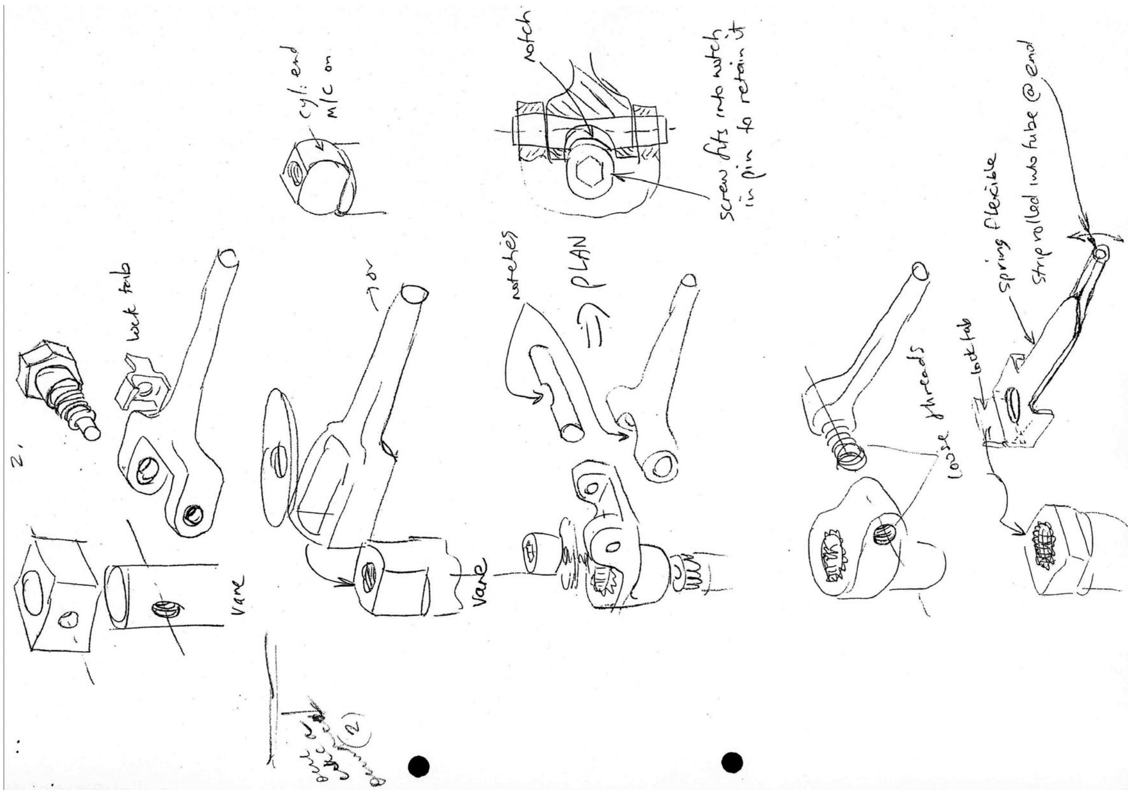
(6) Reference no. 7.2 (S12)



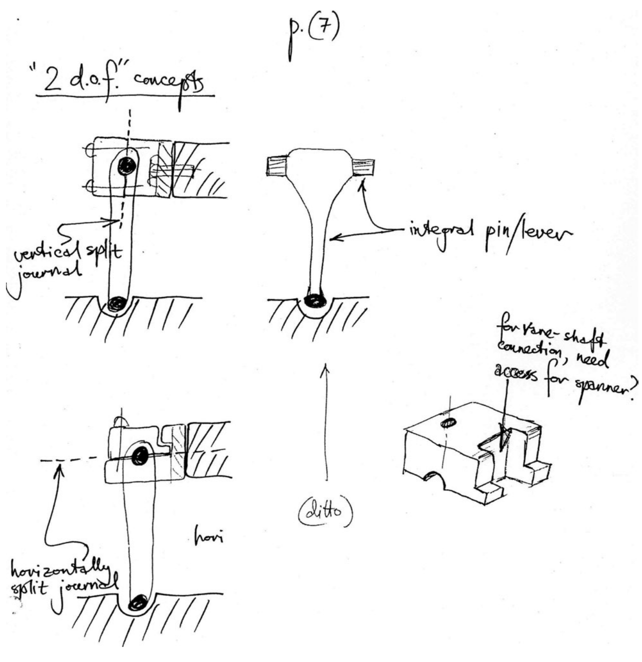
(7) Reference no. 13.2 (S24)

APPENDIX C — EXAMPLES OF PROFESSIONALS' RESPONSES TO CASE PROBLEM

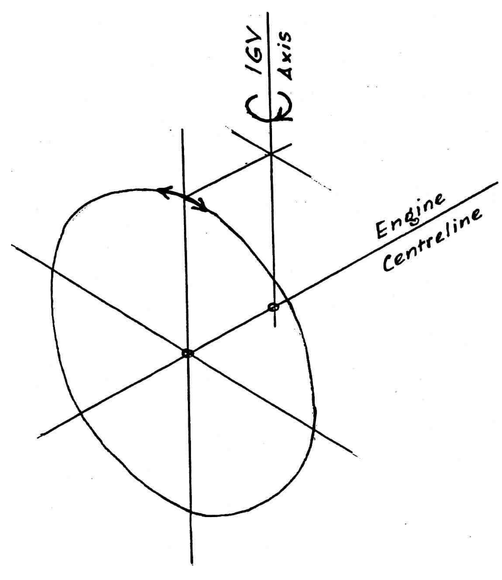
This Appendix contains one page from the notebooks of each of the professionals designated P1, P2, P3 in the paper.



(1) Professional P1



(2) Professional P2



(3) Professional P3