INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

"ISLANDS OF FAILURE IN A SEA OF SUCCESS": THE USE OF CONSTRAINTS AND FAILURE MODE MAPS TO ASSESS THE CAPABILITY OF MACHINES TO HANDLE PRODUCT VARIATION

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ABSTRACT
The approach described here utilises the capability of a constraint modelling environment to map the failure modes of a design. At this stage the modeller can be employed to explore possible design variations against a given goal which does not violate the failure modes. Mapping of the failure modes gives the designer enhanced knowledge of which modes are invoked under certain processing scenarios. This allows the designer to modify the design so that it lies in an area away from the failure mode. The combined failure maps illustrate the functional boundary of a design under variation.

Keywords: *Failure mode maps, constraint-based modelling, processing equipment, design knowledge, mechanisms.*

1. INTRODUCTION
Systems and subsystems of production equipment are often designed for a specified task. However global market pressures mean that manufacturers are gearing towards mass customization [1]; at a shop floor level, this means over the life span of the equipment for it will be required to perform different variant tasks. These may include dimensionally changed product or increased performance requirements. The construction of the system may mean the certain elements such as machine size or drive locations, are constrained adding to the difficulty of handling product variation. The core thoughts of the approach presented in this paper can be summed up by a quotation from a British actor and writer Jim Dale MBE: "You cannot learn anything from success, you only learn from failure". Contemporary research has implied the benefits of learning from failures in product design [2]. Elaborating this, if you redesign a system and it works first time, then the only knowledge you have is the success. If the design fails you can derive information from this failure: what the failure mode(s) are, and/ or which variable or cluster of variables in the system, is causing the failure. Learning from these are the stepping stones for the next iteration of the design process. The construction of the equipment may mean certain elements, such as the machine size or drive location, are constrained and this adds to the difficulty of handling variant products. It is useful to know the functional limits of sub-machines and mechanisms. The use of constraints has proven to be useful in product design [3], performance evaluation and the optimization of manufacturing systems [4]. The combination of constraint-based methods and failure analysis seems to offer an approach for the redesign of systems.

The designer needs to follow procedures to evaluate potential solution variants [5]. These can be investigated using modelling tools such as constraint modelling in combination with the failure mode maps (FMMs). The generation of FMMs allows the designer to assess which failure modes are restricting a solution variant. With this knowledge the designer can assign the variant to a functional area where the failure mode is not violated. The approach used here requires the generation of a parametric model of the machine under investigation. Mechanisms within the machine need to be modelled within their environment so they can be optimised. The failure modes and bounding limits of the mechanism are associated with the model. The failure modes for the mechanism are investigated individually. Suitably chosen elements from the mechanism are disturbed (adjusted) and the effects explored. In particular, some parameters can be changed automatically and the model is then run until the mechanism reaches the goal of performance. This is automatically searched by routines within the constraint modeller. When the mechanism runs without violating a failure mode, the configuration is recorded. The modeller selects the next start point and repeats the process. Once all start points have been selected, the next failure mode is selected and the process repeated. The output from the process produces a map of the failure modes. The combination of the boundary of the failure modes gives the functional limits of the variation of the mechanism.

The FMMs can be plotted individually and overlapping. These can then be simplified by removing failure modes which are not invoked because another failure mode has precedence. The FMMs can then be used to create a strategy to modify the design of the machine to allow for expected variation to an acceptable region of performance that is acceptable. The approach described in this paper is demonstrated through the example of a four bar mechanism and is applied to a case study from a processing station.

2. BACKGROUND.

2.1 Constraint-based design

Constraint based approaches have been employed across the design and development process. For example O'Sullivan [6] who presented an interactive constraint-based approach to supporting the designer at the conceptual design stage. He proposed a computational reasoning environment based on constraint filtering as the basis of an interactive conceptual design support tool. Mullineux et al [7] describe how a constraint modelling environment can be used to aid the conceptual design stage by searching for solution principles and evaluating these principles against the constraint rules. Holland et al [8] have developed an add-on constraint based design technology for Autodesk inventor to aid the designer at the conceptual design stage. Matthews et al [9] presented an approach for investigating performance envelopes of systems. Kenney et al [10] proved how a constraint modelling environment could be used to satisfy design constraint for conceptual mechanisms. Fa et al [11] developed a constraint-based modelling system that determined the degrees of freedom of a constrained object operationally in terms of allowed rigid motions of the object. For each new constraint on the object, the allowed motions are reduced using look-up tables. Martinez et al [12], produced a constraint based approach for detailing designs. Their method defined the constraints and geometry of a two dimensional sketch and relates this to the complete dimensioning of the engineering drawing. Parts are dimensioned against given drawing standards. Their approach established whether the system was over or under constrained. Using their dimensioning criteria redundant constraints can be highlighted. Although the underlying constraints for each problem are different, the approaches presented by the above authors show the benefits of investigating design from the constraint perspective.

2.2 Failure mode maps

FMMs are commonly employed in engineering science to graphically illustrate failure regions of properties, and as materials under given conditions. Bull [13] produced FMMs for scratch adhesion tests for hard coatings. The maps were produced in terms of substrate and coating hardness. Trantafillou et al [14] used failure mode maps, defined for foam core sandwich beams, to design minimum weight beams for a given strength. Lim et al [15] produced FMM's for the impact and static loads of foam core sandwich beams. They stated the FMM was employed to avoid specific failure modes or achieve minimum weight design. Petra and Sutcliffe [16] expanded on previous work [14] work to produce FMMs as a design tool for the production of honeycomb sandwich beams. In convention FMM's as with [13,14,15], the whole map area includes is dissected by the failure modes.

The maps presented in this paper relate to mechanism and machine design. They also dissect the design space. They also conclude on area of functionality where the mechanism can be altered with no failure being invoked

3. THE CONSTRAINT BASED MODELLING

Constraints within machine systems usually relate to be the performance and physical requirements of the design or relations between the geometry of parts. When dealing with a system, it is unlikely that individual elements or operations are independent of the other elements. Therefore, the various performance goals and the related constraints must be dealt with concurrently and all their interrelationships taken into account. In design the aim is to find a configuration that satisfies all the imposed constraints as closely as possible and satisfies the performance requirements. The Venn diagram, figure 1, shows four constraints of the system (a-d) visualized as subsets of all possible designs. The feasible solution space is the intersection of all the individual constraint subsets.

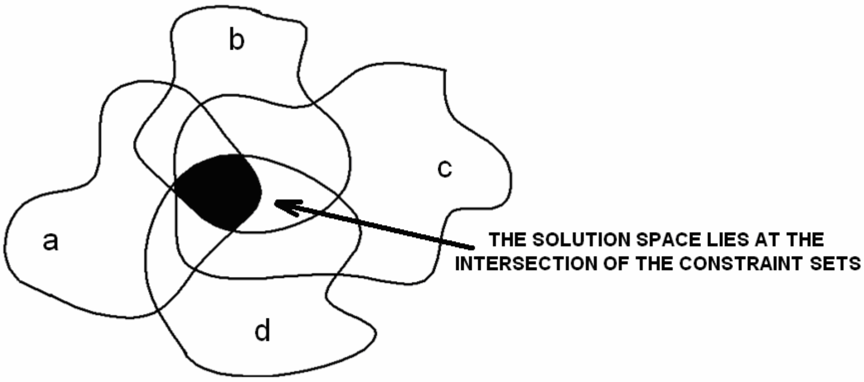

Figure 1 Overlapping sets of constraints

When a problem is under-constrained, there is more than one solution or even infinite possibilities. If the problem is over-constrained, in general it has no solutions, as no intersection exists between the sets. If it is precisely defined there may be a single solution. The constraint environment presented in this paper uses numerical optimization methods for constraint resolution, [17]. Constraints are translated into systems of non-linear equations, and then solved by iterative approaches such as Hooke and Jeeves, Powell's or hybred Newton-Raphson [18]. During resolution, the expression for each constraint is evaluated, and the sum of the squares of all constraints is found. A 'true state' is declared when objective function of the equation is returned as a zero.

4.1 Constraint modeller environment.

The paper uses a particular constraint modelling system [19], although the process could be performed using any parametric modelling package. It has its own user language which has been created to handle design variables of several types, including structured forms to represent geometric objects. The language supports user defined functions. These are essentially collections of commands which can be invoked when required. Input variables can be passed into a function and the function itself can return a single value or a sequence of values. Routines are used to impose constraints using an important in-built command which is the "*rule*". Each rule command consists of a constraint expression between some of the design parameters which is formed so that it is zero when true. A non-zero value is a measure of the falseness of the constraint rule. When rules are used in the construction of mechanisms, the value returned from evaluation of the rule can be used to assess the functionality of the mechanism.

The software environment supports simple wire-frame graphics, such as line segments, circular arcs and solids. Cams profiles in the modeller can be constructed using the B-spline form the curve defined by a set of control points. Solids have been incorporated into the environment by means of the ACIS library of procedures. Geometric entities can be defined in world space or associated with a 'model space'. The model spaces can be embedded within each other, so that they can move with other geometry entities. As an example, consider the representation of an ejection mechanism from a confectionary wrapping machine, which is shown schematically and pictorially in figure 2.

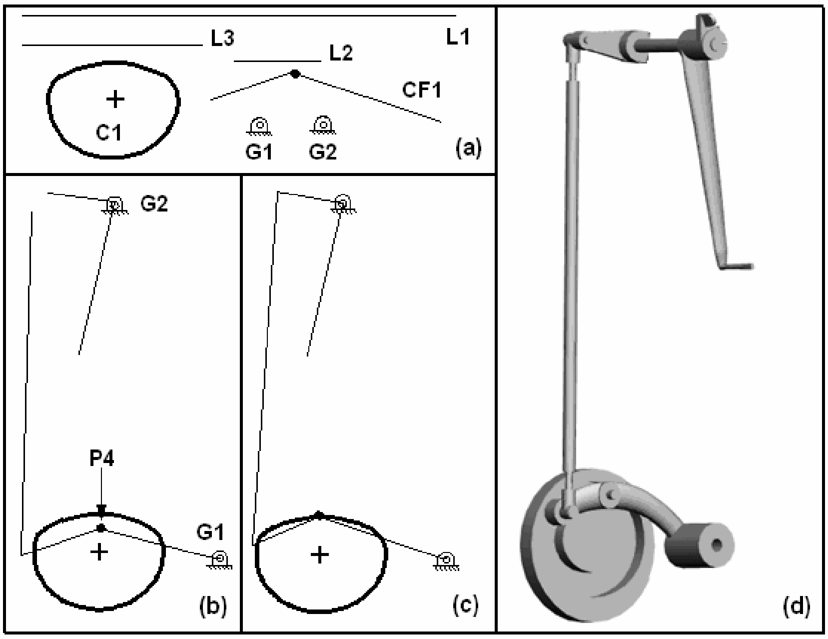

Figure 2 Constraint-based model of ejection mechanism

In part (a) of the figure, the two fixed pivot points 'G1' and 'G2' are specified, the closed curve 'C1' representing the cam, and the line segments representing the four links are defined; 'L1' is the pushrod, 'L2' the link, 'L3' the eject arm and 'CF1' the cam follower.(cf. figure 2). A point 'P4' is defined for the position of the cam follower on the cam follower arm. (represented by as the dot on the cam follower). Initially points 'G1' and 'G2' are embedded in the machine model space. In the example, the model space of the pushrod and 'p4' (M3) are "embedded" in the space of the cam follower arm (M1). The spaces for the link and ejection arm are embedded in M2 together with the cam embedded in machine space. The hierarchy of these model spaces, is shown in figure 3. A partial assembly of the mechanism is achieved by applying the transformations to the links in each space. This is shown in part (b) of the figure. If the space of either the crank or the coupler is rotated, the hierarchy of their spaces ensures their ends remain attached.

To complete the assembly, the ends of the pushrod and link have to be brought together; and the cam follower point 'p4' has to be put on the cam profile. This cannot be done by model space manipulation alone, as this would break the structure of the model space hierarchy. Instead a constraint rule is applied whose value represents the distance between the ends of the lines. The user language has a built-in function '*on*' which returns the distance between its two geometric arguments. To attach the cam follower to the cam profile rule 'a' is employed. With this rule invoked point 'p4' will follow the profile of the cam as the cam model space is transformed.

Rule 'a': `rule(p4 on cam);`

To attach the pushrod and link elements together, rule 'b' is imposed.

Rule 'b': `rule( pushrod:e2 on link:e1 );`

The colon followed by e1 or e2 denotes either the first or second end-point of the line. In order to satisfy these constraint rules, the system is allowed to alter the angle of the model space of the cam. When the rule is applied then the correct assembly is obtained as in part 'c' of figure 2. When the space of the cam is rotated and the assembly of the other elements is performed at each stage, a step-wise simulation of the motion is obtained. If solid objects representing the link are constructed, these can also be included in the model spaces as shown in part (d) of the figure.

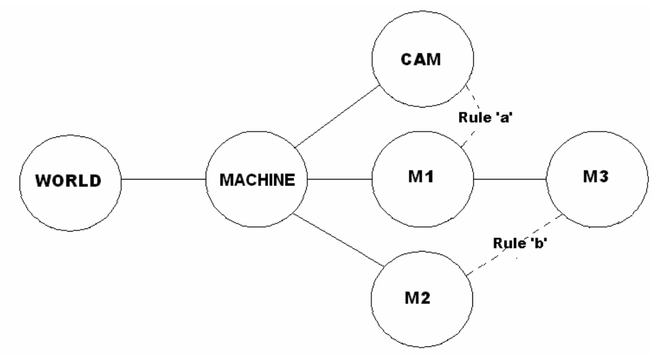

Figure 3 Hierarchy of model spaces for the ejection mechanism

With the mechanism defined, its functionality can be explored. There are instances when the mechanism functions correctly; conversely there are instances where the mechanism will fail. It is the exploration of the areas where the mechanism works or fails that will allow the possibilities of creating designs that can cope with new product variation.

4.2. Failure mode map construction

This section explains the process of map construction. For this purpose the example of a four bar linkage is used (figure 4a). The approach is to firstly construct a parametric model of the mechanism within the constraint modelling environment. Figure 4b shows such a model, for the four bar linkage. The model has been constructed using the methods described in section 3. The mechanism is driven by the rotation of the crank on the left around it base pivot. The modes of failure for this mechanism are taken to relate to the path travelled by the point offset from the coupler. Failure is deemed to occur if the path passes outside of the rectangular box shown in the figure, or if the mechanism fails to assemble. This approach takes a known working model and 'disturbs' the design until it reaches the failure points. The factors which were allowed to change are the lengths of the driven and crank links. These were incrementally changed and their failure recorded.

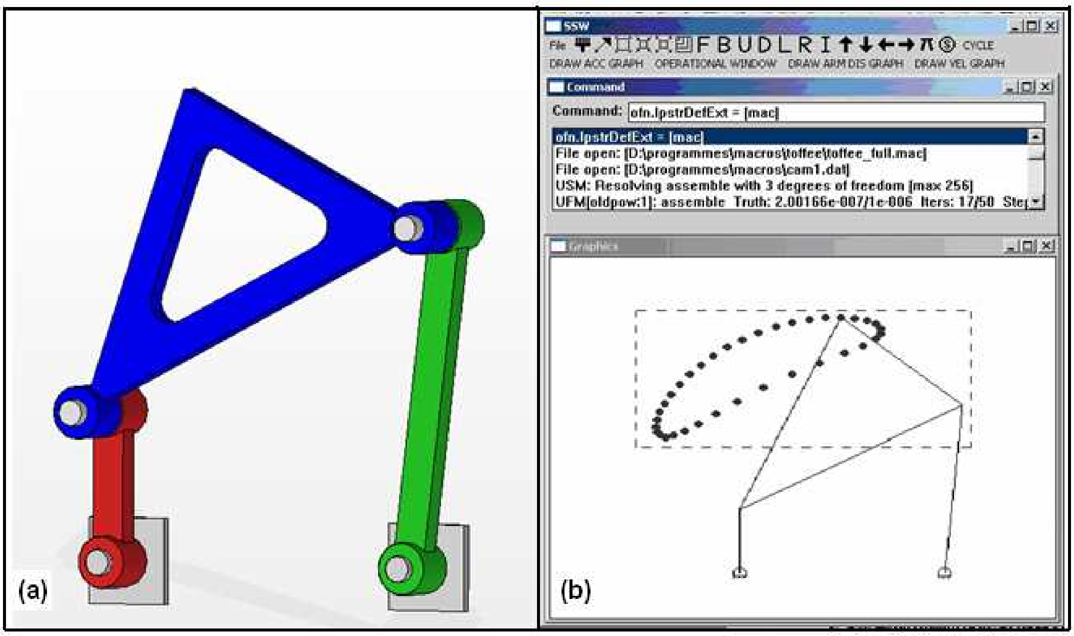

Figure 4 four bar linkage

Strategies were been developed within the modelling environment to detect the various failures of mechanism.

- *Truth*: To check for mechanism deconstruction the 'truth' function in the constraint modeller was utilized. The constraint modeller performs assemblies by minimizing the error in constraint rules which represent the distance between parts. Its ability to do this can be used the access the success of failure of the assembly. Once this *"assemble"* function has been invoked, the inbuilt function *"truth"* can determine its success. It returns the final sum of the rule values; if this is greater than zero then the mechanism has failed.
- *Hard limits*: The models are drawn within the modelling environment. The language allows the use of logic to detect if an element of the model has reached or exceeded fixed geometrical failure limits imposed on the system. Within the model space limits can be set for the movement of elements. Simple logic can then be employed to investigate the maximum and minimum limits for these elements
- *Embedded solids*: Solids can be used within the environment to detect interaction of elements. The modelling environment has the ability to identify the volumes of the solid objects; this is utilized to measure the volume of the interaction of the solids.
- *Bounded boxes*: Here a box is a rectangular block that contains an object throughout its motion. If the configuration of the mechanism is changed and the motion now falls outside the box it is deemed to fail. While this is crude, it is an approach that is sufficiently reliable for specific applications.
- *Kinematic*: At a higher level the constraint modeller can calculate the restrictions imposed by the first three derivatives of motion. (acceleration, velocity and jerk). Permissible limits for these can be set into the model and simple logic can be employed if these are exceeded.

Figure 5 shows the working regions of the mechanism before the lengths of the driven and crank link cause the mechanism to fail to assemble geometrically to becomes disassembled at some point through the motion of the mechanism or assembles in the wrong mode that a configuration different to original constructed. A line which runs through zero on the drive crank axis, is produced, as the mechanism does not function if the crank length is zero. The grey zone is the functional area. Any further failure modes added to mechanisms function constrain the link variability further.

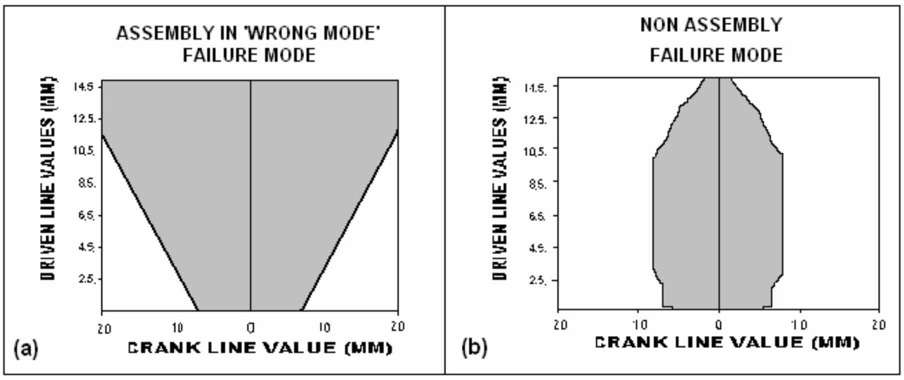

Figure 5 Mechanism 'non assembly' and 'assemble in wrong mode' failures.

Figures 6 show the individual failure maps for the specific failure mode associated with the bounding box, with the white zone being the failure areas.

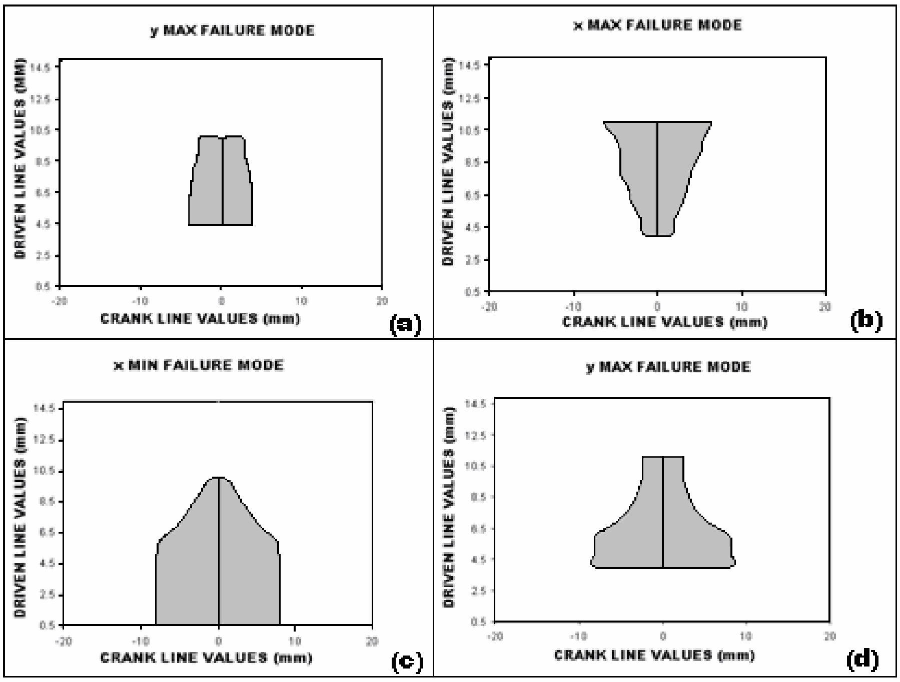

Figure 6. Box failure mode maps

What becomes evident when assessing such a simple mechanism against failure modes is how complex the failure assessment environment actually is. When all the failure modes are combined together (figure 7a), one can see the failure area where changes to these two elements will not function. With all FMM overlaid, the next stage is to remove un-invoked failure modes. In figure 7b these are mechanism collapse and deconstruction. Then to remove failure points which are not invoked. Within Excel or Matlab these points can be highlighted on the graph and removed from the original dataset. The points of overlap can be identified against individual FMM and addition points added to the data set to produce the separation lines of the dominate failure modes. The result of this process is can be seen in Figure 7b.

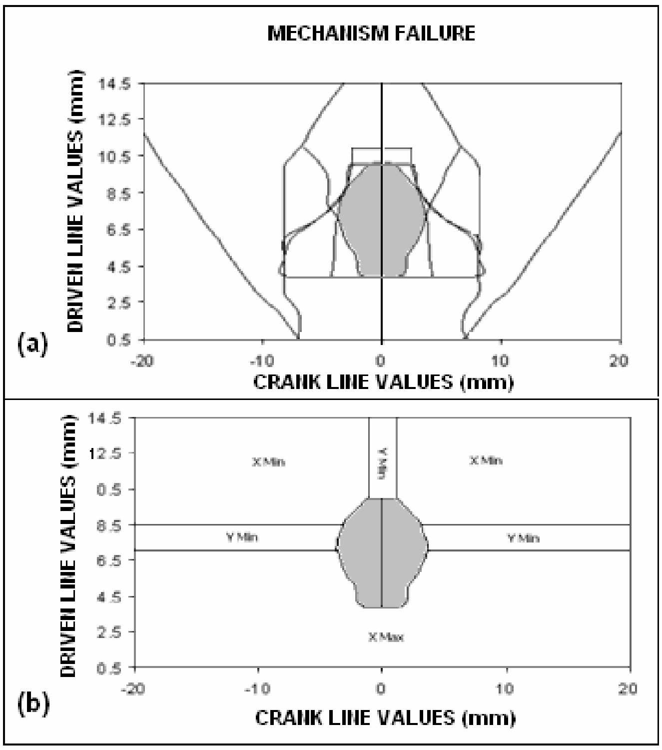

Figure 7 Failure mode diagrams overlapping

5. CASE STUDY EXAMPLE

The following example is an elevator sub-mechanism from a packaging station. The mechanism is required to push the product through the packaging medium to the wrapping station. The elevator of the machine is required quickly to return to the start position, so not to interact with other parts of the machine. A change to a lower value product has meant that the processing cost has increased, to keep the processing costs in line with the original product; a double of processing speed is required. This has two implications on the product: increased speed can cause damage to the packaging medium on transfer, and the increased acceleration of the mechanism induces vibrations into the rest of the machine. Figure 8 shows a wire frame model of the elevator mechanism constructed in the constraint modeller environment. The mechanism has four parts: the cam ‘C1’, the cranked cam follower arm ‘L1’, the elevator ‘L3’ and the connecting rod ‘L2’. The elevator runs on a slideway so in the model it is constrained to only move vertically. Previous investigations have shown that acceleration greater than a particular value cause problems to similar processes, so this has been defined as the failure limit.

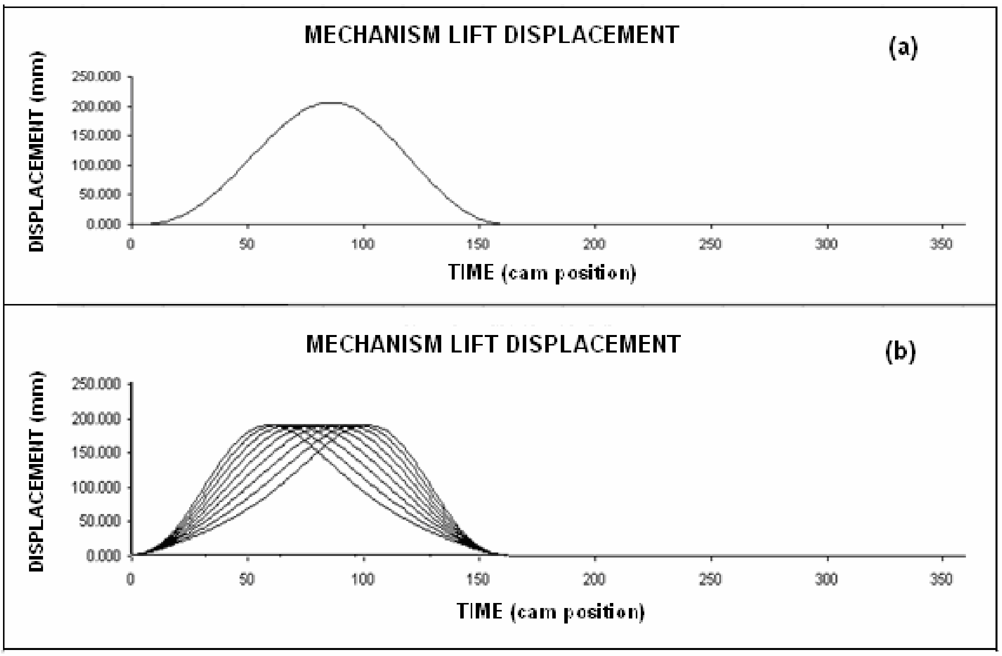

Figure 8 Lift displacement profile graphs.

Figure 8a shows the displacement profile for the lift mechanism. The timing for the lift relates to the rotational movement of the cam. Before considering any modification to this profile the functional constraints have to be defined. The displacement distance is fixed as it is required to transfer the product from the base of the machine to the packing height. The start and stop points are also critical as they are timed with other sub mechanism within the machine; the product is requires to be in place by the time the cam has reached 150°. This leaves the position of the peak of the lift profile as the only factor that can be modified. The lift profile can be described by a sinusoid. To adjust the peak position, the sinusoidal motion law was modified. This modification was calculated to give peak positions from 10° to 150° cam timing. Some of the modification can be seen in Figure 8b. The points from the modified sinusoid are employed as the drive geometries for the end effecter of the elevator. As the elevator is moved, the model space where the cam would be positioned is rotated. With each movement of the elevator a point is transfer from the end of the cam follower into the cam vacant model space. Each cam profile was saved sequentially as text files. These files were read back into the modeller and the run as the drive cam. The acceleration, jerk and velocities were then logged for against each profile. These values were then used to construct the FMM (figure 9).

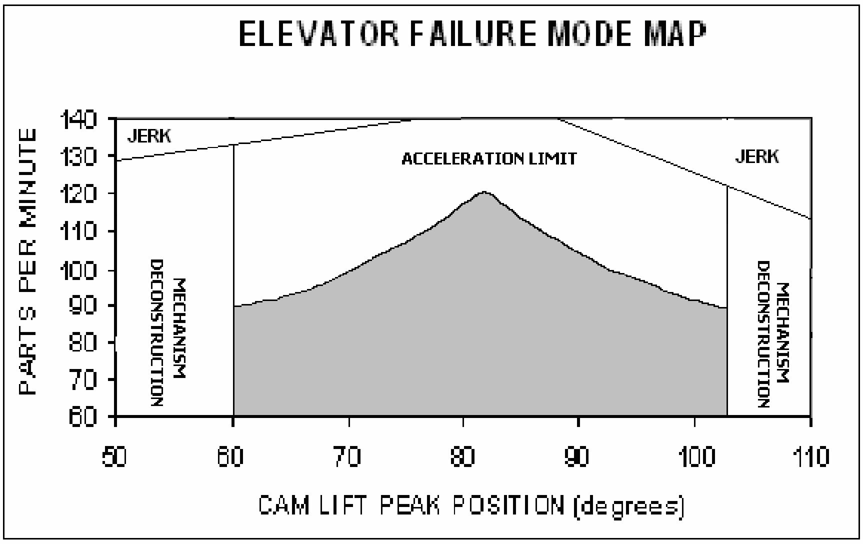

Figure 9 Failure mode map for the mechanism.

The acceleration and mechanism deconstruction failure modes are the dominant factors in failure of the mechanism, so only these are considered. By inspecting the FMM is it evident that the goal of doubling the production speed to 130 parts per minute is impossible as the acceleration failure mode is invoked. What can be seen is that if a peak profile of 82° was used, it would be possible to increase the production to 118 parts per minute, although this would mean running the process at its limit.

6. CONCLUSION

With subsystems designed for a particular purpose it may be required over, the life span of the mechanism for it to perform a different task, whether this may include dimensionally changed product or increased speeds. The construction of the mechanism may mean the certain elements such as machine size or drive locations, are constrained adding to the difficulty of handling product variation. This paper has introduced a constraint modelling environment and an approach which allows a FMM to be created, illustrating the functional boundary of mechanism variation. This map indicates which failure mechanism, are causing the mechanism to fail under a given scenario.

This approach gives the designer enhanced knowledge of the system; with the failure identified for a given scenario, if offers the potential for the designer to modify the design to a variant which does not violate this failure mode. The boundary state produced by the combination of the failure mode maps are the limit conditions of functionality for the mechanism. The paper illustrates the approach using a simple case study of an elevator mechanism. Using cam profiles and parts per minutes it was evident the goal of increased production speed was not attainable but the best solution could be indicated from the map. A current investigation using the approach described is being performed to assess the capabilities of food processing equipment to cope with product variation.

ACKNOWLEDGMENTS

The research work described in this paper has been carried out with the support of Department of Environment Food and Rural Affairs (DEFRA) research grant FT1106 given as part of the Food Processing Faraday.(FPF-KTN) This support is gratefully acknowledged together with that of other collaborators.

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