# DESIGN OF AN AIRCRAFT BRAKE COMPONENT USING AN INTERACTIVE MULTIDISCIPLINARY DESIGN OPTIMIZATION FRAMEWORK

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## Abstract

A Multidisciplinary Design Optimization framework called Concurrent Subspace Design (CSD) has been applied to the design of an aircraft brake assembly. This application entailed an interactive implementation of CSD in which design information was obtained using existing industrial analysis software. The optimization problem statement in this study included a number of performance requirements associated with a brake that has been produced for a commercial aircraft. The results indicated that the CSD framework was able to efficiently identify improved designs which met all the constraints imposed on the problem. The designs do not represent practical alternatives, however, because considerations related to production and maintenance costs, which are paramount in industry, were not incorporated into the optimization problem statement.

## I. Introduction

Recent work in the field of multidisciplinary design optimization (MDO) has been inspired by the need to efficiently design highly complex, nonhierarchic systems. These typically involve many mutually dependent disciplines, each of which has some impact on the system design goals. For MDO techniques to be at all beneficial in the design of engineering systems, a number of characteristics of such systems must be taken into account during the development of an MDO framework which implements those techniques. For example, many engineering systems are "mixed," in other words, they contain both continuous and discrete design variables. The ability to accommodate mixed systems is an important feature of an MDO framework and, due to the computational resources typically required by mixed optimization methods, usually necessitates the use of some form of response surface approximation [1]. Also, analysis tools for a variety of engineering systems exist and have been in use for some time, although the design of such systems has not necessarily involved MDO methods. Therefore, it is desirable that an MDO framework be easily adaptable to a variety of existing analysis tools, because redeveloping the analysis to incorporate it into the framework or vice-versa would greatly increase the overall cost of the design process.

An MDO framework called *Concurrent Subspace Design* (CSD) has been applied to the design of an aircraft brake component. CSD is closely related to the Concurrent Subspace Optimization method proposed by Sobieski [2] and modified by Renaud and Gabriele [3] and by Sellar [4]. This study represents a "follow-up" to another CSD application that was based on the same component [5]. For the current case, the optimization problem statement was reformulated so that it would be a more accurate representation of the design problem as practiced in industry.

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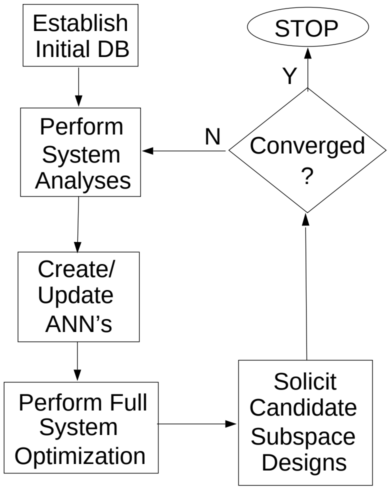

Figure 1: Interactive CSD Framework

## II. CSD Framework

Concurrent Subspace Design is an MDO framework which includes means by which discipline-level designers are provided with information regarding the influence of their decisions on the system-level objective function and constraints. That information is provided by response surface approximations in the form of artificial neural networks. A fully automated, "monolithic" version of CSD has been described in a number of prior papers [6]. During its application to the aircraft brake component described in the following section, an interactive version of the CSD framework was implemented. This permitted the use of an analysis tool that was developed independently of the optimization framework and was not originally intended to be used in conjunction with it.

The interactive version of CSD implemented in this study is illustrated schematically in Figure 1. The algorithm begins with the selection of a set of baseline designs, which are analyzed and included in the *design database* from which the initial system approximation is constructed. The initial database may also include designs that were analyzed during previous studies if any such information is available. Feed-forward, sigmoid-activation artificial neural networks (ANN's) are then trained via the Error Backpropagation method [7] to approximate the design space. A system-level, fully approximate optimization is then performed and results in a single new design. The method of optimization used at this stage is a hybrid technique that combines discrete and continuous optimization and was described in [8].

After the system-level optimization takes place, the subspace designers have the option to add designs to the database. They are allowed to use whatever methods and/or tools they choose in attempting to improve the design. Though it may, is "improvement" does not necessarily take the form of traditional optimization algorithms. Rather, time constraints may limit subspace design to only a few system analyses, intuition, "rules of thumb," and the like. In the current application, subspace designers were able to perform manual design studies using the full system analysis tool, as well as use the neural networks to perform a number of approximate analyses very quickly. At each CSD iteration, the subspace designers can work concurrently and are allowed to contribute as many designs as time permits.

All the designs suggested by the subspace designers, as well as the one which resulted from the previous system optimization, are then analyzed using the full system analysis tool and added to the database. The response surface approximations are then updated to reflect this new information and another fully approximate optimization is performed. This iterative process continues at the discretion of the designers, who monitor progression and determine when suitable convergence has been achieved.

The current implementation of the CSD framework itself is invoked on a Unix workstation with process control developed using Tk/Tcl. It is not necessary that the system analysis tool also be a Unix application; the system analysis for the application described in the following section consists of a PC-based spreadsheet. In this case, design information was exchanged between different platforms using file transfer protocol (ftp).

## III. Application: Aircraft Brake Component

The CSD framework was applied to the design of an aircraft brake assembly. The specific components involved are the "brake stack," "torque tube," and a piston/spring apparatus which actuates the system. The brake stack consists of "rotors," which rotate along with the aircraft's wheel, and "stators," which are keyed to an external landing gear structure and remain stationary during operation. The rotors and stators are circular disks which collectively form a cylinder. The torque tube is the structure to which the stators are keyed; it reacts to torsional and axial loads generated during brake actuation. The purpose of the actuation system is to apply the necessary pressure to the brake to slow or stop the aircraft

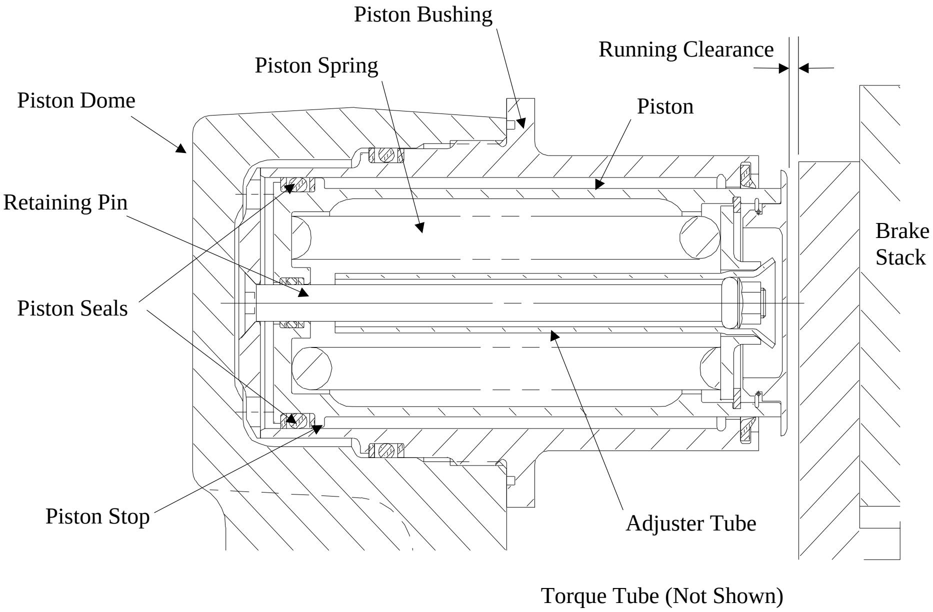

Figure 2: Aircraft Brake System Schematic

during runway maneuvers such as taxis and landings. A schematic of the actuation system appears in Figure 2. During actuation, hydraulic fluid is supplied to the brake through a brake line. This fluid compresses when the pilot depresses the brake pedal, producing pressure on the brake actuation system. This compresses the spring and causes the pistons to extend and push the rotors and stators in the brake stack together. The resulting friction force produces the torque required to slow and stop the aircraft. When the brake pedal is released, the spring extends and forces the piston away from the brake stack, restoring the original configuration of the system. As stated earlier, this component served as the model for a previous CSD application and more thorough descriptions of it and the associated system analysis tool are available in [5].

The system analysis (SA) tool for this system, which is the source of information used to make design decisions, took the form of a Microsoft Excel workbook [9] and was developed by Allied Signal Aerospace, Inc., Aircraft Landing Systems. The workbook which comprises the SA is quite extensive, containing 39 worksheets and thousands of active cells. In addition to the evaluation of equations which compute states, the system analysis also includes "design" considerations, in the form of rule-based logic and user-defined constraints, to a significant extent. It is important to realize that, because the SA was not originally intended to be used in conjunction with an MDO framework, much of what could be considered "design" in an MDO context was embedded into the analysis. In fact, formulating the optimization problem such that *design* decisions were made the by CSD framework rather than implicitly included in the *analysis* proved to be a significant endeavor. Finally, it is noted that all of the design considerations accounted for in the existing tool were associated with meeting requirements (i.e., satisfying constraints); it did not include any optimization capabilities.

The SA tool performs detailed analyses which insure that the displacement of the hydraulic brake fluid is compliant with the actuation system (i.e., no fluid leakage occurs) and determine structural stresses in the spring, piston, and bushing. Those analyses require and produce a substantial amount of information. A relatively small subset of that information, which was identified as critical in the design of the brake component, is represented among the design variables and system states in this study. To create a more realistic, multidisciplinary problem than had previously been considered, simple empirical relationships were used to estimate a number of other system performance characteristics, such as operating temperature and stopping torque, on which design requirements would typically be imposed.

The design optimization problem as formulated contains 14 design variables and 24 states. Compared to the earlier CSD application that was derived from this analysis, the current one reflects

Table 1: Aircraft Brake Component Design Variables

| DV | NAME | TYPE | LB | UB | PIST. | SPR. |
|---|---|---|---|---|---|---|
| $x_1$ | Brake Outer Diameter (in.) | cont. | 12.0 | 20.0 | × | × |
| $x_2$ | Brake Inner Diameter (in.) | cont. | 10.2 | 20.0 | × | × |
| $x_3$ | Rotor Thickness (in.) | cont. | 0.5 | 1.5 | × | × |
| $x_4$ | Number of Rotors | disc. | 4 | 6 | × | × |
| $x_5$ | Wear Pin Length | cont. | 1.46 | 3.5 | × | × |
| $x_6$ | Piston Diameter (in.) | cont. | 1.0 | 2.25 | × | |
| $x_7$ | Number of Pistons | disc. | 5 | 12 | × | |
| $x_8$ | Bushing Stop Thickness (in.) | cont. | 0.05 | 1.0 | × | |
| $x_9$ | Torque Tube Mat'l Option | disc. | 1 | 2 | × | |
| $x_{10}$ | Spring Mat'l Option | disc. | 1 | 4 | | × |
| $x_{11}$ | Spring Outer Diameter (in.) | cont. | 0.5 | 2.5 | | × |
| $x_{12}$ | Spring Wire Diameter (in.) | cont. | 0.15 | 0.4 | | × |
| $x_{13}$ | Spring Free Length (in.) | cont. | 0.4 | 6.0 | | × |
| $x_{14}$ | Spring Rate (lb./in.) | cont. | 200 | 3000 | | × |

an increase in the number of design variables (from 12 to 14), states (from 18 to 24), and constraints (from 8 to 17). The design variables and corresponding variable types and bounds are listed in Table 1. The CSD framework allows for concurrent design at the subspace level by providing subspace designers with quantitative information regarding the influence of their decisions on the system-level objective function and constraints. For this application, subspaces corresponding with the "spring" and "piston" were defined and the design variables allocated between the two as indicated in Table 1.

A primary objective of aircraft design is to minimize weight, therefore, the total weight of the brake assembly served as the objective function for this application. The optimization problem was stated as

$$\begin{aligned}
&\text{MINIMIZE:} && && (1)\\
&W_{total} &=& W_{torquetube} + W_{brakestack} \\
& && + N_{pistons} \times \\
& && (W_{spring} + W_{piston} + W_{bushing}) \\
&\text{SUBJ. TO:} && \\
&g_j &\geq& 0 \quad j = 1 \ldots 17 \\
&x_{LBi} \leq & x_i & \leq x_{UBi} \quad i = 1 \ldots 14
\end{aligned}$$

The objective function is identical and the design variables very similar to those used in the earlier study that was based on this brake component. The states and constraints, however, have been modified considerably. In the previous application, the only constraints were margins of safety associated with different stresses in the piston, spring, and bushing. Those margins were computed by the system analyses and were the only system states, aside from the individual component weights, that had any bearing on the design problem.

Of the 24 states considered in the current study, five were again the component weights that contribute to the total weight $W_{total}$. The remaining states were indicators of performance that were used to compute the constraints $g_1 \ldots g_{17}$. Some of these were margins of safety similar to those that had been previously considered. The majority of them, however, were associated with other pertinent customer requirements. For example, the constraints in this problem insured that the brake produced adequate torque to stop the aircraft within a specified stopping distance and did not exceed an allowable operating temperature when it absorbed a given rejected takeoff (RTO) energy. There were also constraints on the physical dimensions of the system to prevent it from protruding beyond "envelopes" dictated by surrounding components of the aircraft's landing gear. These constraints enabled the optimization problem statement in the current study to embody more of the design requirements that exist in practice. The "customer requirements" considered for this CSD application were adapted from a brake that has actually been produced and is in use on a commercial aircraft. This facilitated assessments of whether design modifications made by the CSD algorithm were sensible in the context of minimizing weight and whether the modified design would be practical and/or feasible given those requirements.

## IV. Results

The initial database generated for this design problem contained 38 designs. One of these was a baseline design that served as the "starting point" for the CSD process. Every other design was obtained by perturbing one of the 14 design variables listed in Table 1 away from its baseline value. Three different values (aside from the baseline), approximately evenly distributed between the appropriate bounds, were selected for each of the continuous design variables. Also, both torque tube material options and all four spring material options were represented in the initial database. The total weight of the brake component for the designs in the initial database ranged from 403.7 to 669.1 lb., while the mean and standard deviation were 581.3 and 47.6 lb., respectively. None of these initial 38 designs were feasible.

The baseline design in the initial database was that of the brake component as it has actually been produced, which had a total weight of 589.4 lbs. Strictly according to the constraints posed for this CSD application, this design was actually infeasible. The reason for this is that one of the constraints enforces a minimum weight of the brake stack in its worn state. The threshold value is that which corresponds to the allowable operating temperature being reached, but not exceeded, when it absorbs a given rejected takeoff energy (RTO). The latter is a function of the aircraft's size and speed and thus is essentially specified by the intended use of the aircraft. In this study, the "thermal analysis" consisted of an emprical relationship between the stack weight, operating temperature, and RTO, according to which the brake stack would have slightly less than adequate weight after it had worn. Obviously, much more detailed and accurate thermal analysis methods are used in practice.

### Design Improvement via CSD

Twelve CSD iterations were performed in this design study and a convergence history of the total weight of the brake component is illustrated in Figure 3. The dotted line and circles on the figure indicate the total weight value obtained from the neural network response surface approximations that are used during the full system optimization at each iteration. The solid line and diamonds reflect the weight as computed using the full system analysis. Recall from Section II that the result of each iteration is not analyzed until *after* that optimization is complete, so some discrepancy between the two values is not unexpected. As can be seen in the figure, the first iteration significantly decreased the total weight to 327.5 lbs.

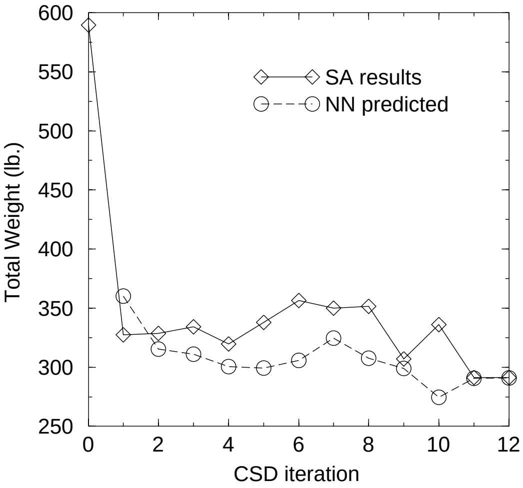

Figure 3: Total Weight Convergence History

Although the design obtained from the first system optimization reflected an improvement in total weight compared to any of the designs in the initial database, it was still infeasible as a number of constraints were violated at that point. Thus, the efforts of the subspace designers were focussed primarily on satisfying the constraints rather than reducing the weight further. As the subspace design studies were performed manually, however, each subspace designer modified the design to address only one or a few individual constraints at a time. Throughout much of the remainder of the process, the total weight of the brake component fluctuated between 320 and 350 lbs. as the design was constraint-driven to a significant extent. A number of the constraints were active and/or violated at different times as the design progressed, and the subspace designers continued to select designs accordingly during each iteration.

Figures 4 and 5 show convergence histories corresponding to two of the system states that were constrained for this problem. As mentioned earlier, one of the constraints required that the weight of the brake stack after it has worn be sufficient to absorb a given amount of energy without its temperature becoming excessive. For this application the minimum worn stack weight was 88.7 lbs., which is indicated by the dotted line on Figure 4. That figure shows that the associated constraint was one of the primary drivers for this design, as nearly every iteration resulted in a point at which the neural network approximations predicted it would be active. This is a logical re-

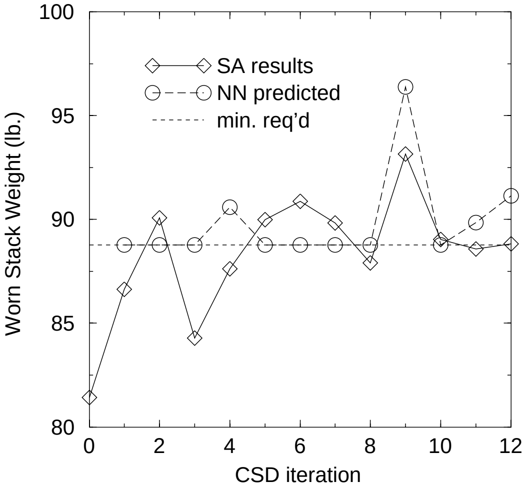

Figure 4: Worn Stack Weight Conv. History

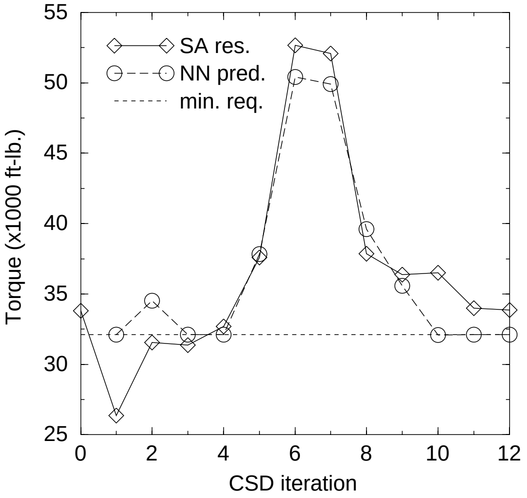

Figure 5: Torque Convergence History

sult considering the overall goal was to minimize weight.

A convergence history of the torque produced by the brake is illustrated in Figure 5. For this application the torque was required to be at least 32,100 ft-lbs in order to meet the customer-specified stopping distance. This constraint also played a role in the design process, as the "over-design" which resulted in much more torque than necessary was eventually corrected as the components of the brake system were sized to minimize weight. As can be seen in the figure, the design converged to a point at which the neural network approximations predicted this requirement would be met exactly, while the design actually provided some leeway in that regard.

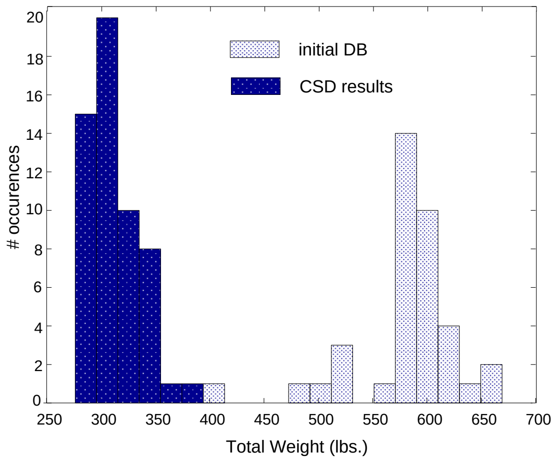

Figure 6: Total Weight Distribution

After the 11'th CSD iteration the total weight had been reduced to 291.4 lb. There was a slight violation of one of the component margins of safety at that point, which the "spring" subspace designer was able to remedy while only increasing the weight by 0.6 lb. The result of the 12'th iteration was nearly identical to that of the 11'th; the difference in total weight between those two designs was less than 0.1 lb. The process was thus terminated at this time. The "best" design in the database was the last one submitted by the "spring" subspace designer, which had a total weight of 292.0 lbs. and satisfied every constraint.

Throughout the course of the CSD process, a total of 55 new designs were added to the database. These designs represent the results of the fully approximate, system optimization and those submitted by the two subspace designers at each of the 12 iterations. The ability of CSD to identify improved designs was evident in the distribution of designs at the termination of the process. This is illustrated in Figure 6, which shows a histogram of the 93 total weight values in the final database for this application. The lightly shaded bars correspond to the 38 designs that were in the initial database, while the darker bars are associated with the 55 designs that were identified during CSD. As can be seen in the figure, every design obtained during CSD had a lower total weight than any design in the initial database. The range of weights amongst the former group was also much narrower than that for the latter, indicating that the algorithm located a desirable region of the space quite efficiently. Finally, a result that is not manifest in Figure 6 is that while none of the designs in the initial database were feasible, a dozen of the designs obtained during

Table 2: Design Distribution Comparison

| | INITIAL DB | CSD RESULTS |
|---|---|---|
| mean $W_{total}$ (lbs.) | 581.3 | 312.3 |
| min. $W_{total}$ (lbs.) | 403.7 | 276.3 |
| max. $W_{total}$ (lbs.) | 669.1 | 389.8 |
| $W_{total}$ std. dev. (lbs.) | 47.6 | 22.9 |
| # feasible | 0 of 38 | 12 of 55 |

CSD were. A comparison of the distributions of these two sets of designs is summarized in Table 2.

Assessment of CSD Results

As mentioned previously, the best design in the database at the conclusion of CSD was one submitted by the "spring" subspace, which satisfied all the constraints and had a total weight of 292.0 lbs. As the difference in weight between that design and the baseline design, which had a weight of 589.4 lbs., would suggest, the CSD result entailed considerable modification to the brake component as it has been produced. It was determined that purely in the context of engineering analysis, the CSD result represents a feasible, viable design, as it is compliant with the required torque, operating temperature, acceptable stress levels, etc. In practice, however, the brake component is not designed for absolute minimum weight. Thus, the design obtained through CSD is not a particularly *practical* one due to a number of other considerations that were omitted from the objective function and constraints in this study. Some examples of this are discussed below.

Recalling Equation 1, five individual components contributed to the total weight that served as the objective function in this study. The weights of each of those components at the baseline (production) design and the "best" design among the CSD results are listed in Table 3. Of the nearly 300 lb. difference between the two designs, approximately 280 lbs. is accounted for solely by the torque tube. This difference is largely attributable to the fact that CSD "switched" the torque tube material from steel to titanium, which was certainly sensible given that weight was the only consideration. In practice, however, a titanium torque tube would not be used on a commercial aircraft because it is substantially more expensive than a steel one. It was determined that if a steel torque tube were used and the design otherwise configured exactly as specified by CSD, its total weight would increase from 292.0 to 403.7 lbs. This considerable discrepancy is a definitive statement that cost considerations, which were neglected in this study, are a primary design driver where commercial applications are involved. The CSD algorithm also selected titanium as opposed to steel for the spring in the brake actuation system.

Table 3: Individual Component Weights (lbs.)

| | BASELINE | FINAL |
|---|---|---|
| Brake Stack | 102.6 | 109.5 |
| Torque Tube | 419.6 | 140.8 |
| Piston | 2.58 | 1.51 |
| Bushing | 6.99 | 4.37 |
| Spring | 1.62 | 0.071 |
| TOTAL | 589.4 | 292.0 |

The results also indicated that regardless of its material, the weight of the torque tube can be reduced if the overall length of the brake stack is decreased and its cross-sectional area increased. This is because the torque tube is keyed to the stators in the stack, and thus its overall length (and its weight) increases with the length of the brake stack, which is determined by the number and thickness of the individual rotors and stators. Given these relationships, the CSD algorithm increased the cross-sectional area of the brake stack and reduced the rotor thickness by over 36%. The rotors also become thinner as the break wears. It was determined that while the rotors as configured by CSD were sufficient to last the specified number of "landings per overhaul," they would have to be replaced at that time. Conversely, the rotors as currently produced are designed such that they can be refurbished (the wear surfaces are machined off) after the initial service interval and still be thick enough to remain in use. Thus, practical considerations omitted from the problem statement in this study include not only production costs, but maintenance costs as well.

The weight reductions in the piston, spring, and bushing reflect a difference between the design philosophy that exists in practice and that which is implemented by CSD. The latter method incorporates *optimization* which, in this case, was used to minimize weight. The effect of this strategy was to reduce a number of physical dimensions, such as the spring wire diameter and bushing stop thickness, until stress levels in the associated components reached their allowable limits. Conversely, while weight reduction was an objective when the brake component was designed for production, this does not mean that the associated design is optimal in that regard. Given that these components reflect a relatively small portion of the aircraft brake component's total weight, the typical approach is to identify a design that is feasible and "weight-competitive." In other words, as long as the assembly is light enough to please the customer, no effort is made to reduce the weight further once all the requirements have been met, even though indications may be that a few pounds can still be cut. Finally, when component stresses are a primary design driver, the brake consumer (aircraft manufacturer) and *their* customers (airlines) may feel that increasing the safety margin between the operating condition and constraint boundary is worth a small "price" in additional weight.

## V. Summary

An MDO framework referred to as Concurrent Subspace Design (CSD) has been applied to a problem that is based on the design of an aircraft brake assembly. The system analysis associated with this application consisted of an industry-developed software tool that cannot be readily integrated into traditional optimization methods. CSD was implemented in an interactive fashion in which the existing analysis tool was used to provide design information without excessive modification to either the analysis or MDO software. The CSD framework had previously been applied to a similar problem that was based on the same physical system. For the current application, the design optimization problem was reformulated to include additional constraints, which were based on performance requirements that are prevalent in practice.

The total weight of the brake assembly served as the objective function for the design optimization performed by the CSD framework. The weight was minimized subject to a number of "customer requirements" that were adapted from a brake that has been produced for use on a commercial aircraft. CSD was able to identify a number of designs for which the weight of the brake assembly was reduced significantly and this was accomplished using a reasonable number of system analyses. The "optimal" design obtained through CSD met all the imposed performance requirements and thus can be considered feasible for this application. It would be of little value in a practical setting, however, because important cost-related considerations were not taken into account in posing the problem.

These results are encouraging in that they demonstrate the ability of the CSD framework to identify designs which are improved according to the objectives and requirements posed for a particular problem. The considerable differences between the minimal-weight and production designs for this component illustrate the necessity to state practical design problems in an intelligent and judicious manner when applying MDO methodology.

## Acknowledgements

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