Design and Analysis of a Modern Human Centrifuge

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The design and analysis of a human centrifuge for Authentic Tactical Flight Simulation is described in this article. An iterative process between 3D CAD design and FE modeling techniques was performed to maximize the efficiency of the design by minimizing the inertia of the rotational system without compromising the stiffness and bandwidth of the structure. Using these techniques together with dynamic modeling, the goal of a natural frequency of 10 Hz and a bandwidth of 3 Hz was reached. Performance tests with the final control algorithms in the software proved the superior controllability of the system.

A Human Centrifuge, such as ETC's Authentic Tactical Flight Simulator (the ATFS 400), is a dynamic device that simulates the G-forces and dynamic flight behavior of a modern, agile fighter airplane. Fighter aircraft are limited with respect to the maximum G-forces they are allowed to experience over time and have to return for depot level maintenance if this level has been exceeded.

Alternatively, a human centrifuge is designed and built to deliver G forces at the edge of the performance envelope of an airplane all day long. Therefore, an extremely thorough analysis has to be performed to achieve maximum strength and the required stiffness while minimizing inertia to provide performance. ETC took the following approach:

Structural Analysis – Past Problems and Lessons Learned. The software tools used for Finite Element Analysis (FEA), such as ANSYS have improved tremendously in the last 20 years. The first centrifuge arm built by ETC in 1985 underwent an FEA using a 16-element model with 6 degrees of freedom for each node, which total 96 degrees of freedom.

The next generation centrifuge was analyzed with in-house software capability. The speed and storage capability of PCs was insufficient to go into a detailed analysis of the entire system. Details had to be investigated separately.

In the meantime, the software and computer capabilities have increased such that FE analyses can involve much more detail, actually down to welding seams. ETC's latest centrifuge arm, for the G-FET II ATFS 400, was investigated with a model having over 97,000 elements and 559,000 degrees of freedom.

Structural Analysis – 3D modeling. The latest generation of ETC's Human Centrifuges, now used as Tactical Flight Simulators, undergo such detailed design and FEA to not only assure that the natural frequency and stiffness goals are reached, but also to minimize the inertia and provide the performance of a modern aircraft.

The ATFS 400 arm was created by means of an iterative 3D modeling/FEA process. The 3D modeling is used to assure manufacturability, avoid interferences, track the mass and inertia of every component, and to generate the detailed drawings necessary for fabrication. The mass and inertia information, along with any manufacturability issues, are passed forward to the FEA while all configuration issues are passed from the FEA back to the 3D model.

While the 3D model is the centerpiece of the engineering process, it is really only one small aspect of the complete process ETC uses to get from inception to factory acceptance. The result of following this process is a documented arm, which is lighter than all previous arms, has the required natural frequency of 10 Hz and has the stiffness required to achieve a bandwidth of 2.75 Hz in the entire rotational system.

Structural Analysis – FEA. A detailed FEA was performed on the arm, the roll ring and gondola. Since these are all parts of the rotational system, their mass and stiffness directly affect the performance of the centrifuge. Reducing mass while retaining stiffness and maintaining strength allowables is the challenge addressed by FEA.

Other items examined with FEA include the pedestal, the embedded foundation fixtures and the motor and gearbox skids. While these items are non-rotating components, the importance of mass and inertia are diminished. Nevertheless, the stiffness delivered by these components directly affects controllability of the system.

The FE model and the obtained results for the rotating components were used to drive the early design of these components. Design changes were brought into CAD to track the inertia and into the dynamic modeling to check the kinematics of the system and to identify peak loading conditions used to generate load cases for FE analysis.

The chief results sought for the rotating components included the stresses for comparison with material allowables, natural frequencies of the basic modes of vibration for a measure of the components' stiffness and the resulting center of gravity and mass inertia. While the stresses of the nonrotating components were checked, the chief result sought was the natural frequencies of the basic modes of vibration. The goal for each component was to maximize its stiffness by maximizing the natural frequencies while minimizing the mass and mass inertia and keeping stresses below the allowed levels.

Additional results examined for each component were the strains. These were used for direct correlation with the dynamic strain gauge testing results, discussed below. This correlation was performed to confirm stress results and to validate the FE model.

As the design matured, the CAD models were used to drive the design providing manufacturing and best-fit solutions. These changes were fed back to the FEA and validated. An example of a 3D CAD model is depicted in Figure 1. The corresponding meshed FEA model is shown in Figure 2 and a contour plot of some analysis results is shown in Figure 3.

Structural Analysis – Dynamic Modeling. For prediction of dynamic behavior and definition of load cases, ETC used a dynamic modeling software package, MSC.visualNastran Desktop Motion. These models can be rapidly changed when necessary. Predicted weights and inertias of the various components were tabled in Excel spreadsheets and constantly tracked and up-dated as the design progressed. The kinematic conditions, along with any required forces and moments generated from this motion analysis that lead to peak loading scenarios over the various motion profiles, were transferred to the FE model as load cases for analysis.

Figure 4 shows an example of a MSC. visualNastran Desktop Motion simulation with the G-graph as the desired input and the torque requirements as the output.

Reliability Analysis. The reliability analysis of the ATFS 400 was performed using Relex® software. Reliability predictions and MTBF calculations provided the basis for reliability evaluations and analyses. The software package supports MIL-HDBK-217 and has a large library of parts included. The electrical and control system for the ATFS 400 is relatively sophisticated. Thus, it would not have been possible to predict the reliability of the device without using a reliability analysis software package

Choosing only quality components having high reliability is clearly the first step in producing a reliable system. Thus, a high reliability prediction was achieved for the ATFS 400, which was verified through months of rigorous factory testing.

Stiffness of the Rotational System. The rotational system is mounted to a pedestal via a bearing system. This pedestal and its supporting foundation have to be very stiff. Therefore the pedestal and numerous sub-systems also underwent FEA. A high natural frequency (approximately 50 Hz) was reached for the ped-

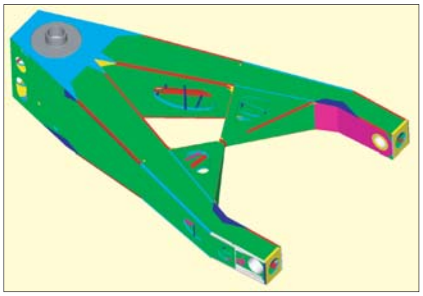

Figure 1. The 3D CAD model of the arm yoke.

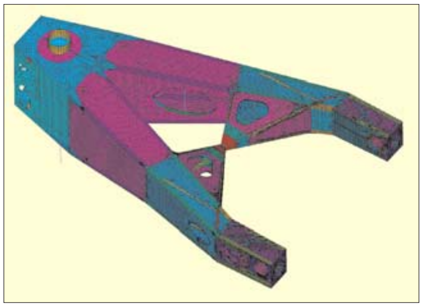

Figure 2. The FE mesh of the arm yoke.

estal achieving an overall system natural frequency of approximately 8 Hz.

To control the system, a high bandwidth had to be achieved. To achieve this goal, the following components of the rotational system underwent intense analysis:

- Structural components (pedestal, arm, roll ring, etc.)
- Main gear reducer
- Drive shaft
- Gimbal drives
- Control system

The structural system, including the pedestal, arm, roll ring and gondola frame underwent a detailed FEA as discussed above.

The main gear reducer is a standard series, bevel helical gear reducer having special, high tolerance gearing and extremely low backlash. All gearing is heat treated and ground for maximum performance and torque capability. The maximum output torque is 1.2 million ft-lbs. The diameter of the drive shaft was selected to make it stiff against bending due to the overhung load, which also provided torsional rigidity.

The gimbal gear reducers are of the cycloidal type. They were selected for the zero backlash performance and their extremely low weight to torque ratio. They are 'flying' at a 25 ft radius at the end of the arm where their mass is playing a significant role. Every pound becomes 15 pounds at the design level of 15 G. The control system was designed to achieve a maximum transport lag of 150 msec.

Although ETC worked with the leading manufacturers in the marketplace for these components, it was still crucial to verify the component stiffnesses with in-house tests. Furthermore, the predicted deflection results of the arm, which was designed and analyzed in-house, were validated in static and dynamic tests.

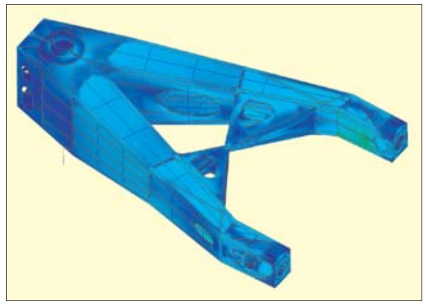

Figure 3. One FE result for the arm yoke.

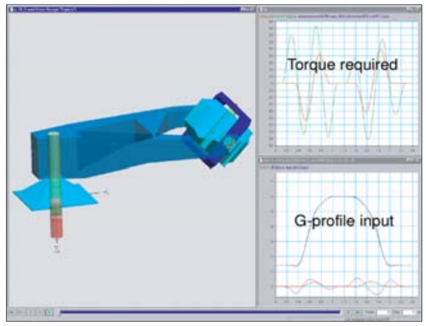

Figure 4. The dynamic model with torque and G-graph.

In this test, the high-speed coupling of the unit (between the motor and the gearbox) was fixed (Figure 7) and then a tangential load was applied at the end of the arm and measured using a load cell. Measuring the rotational deflection at several locations along the drive train and on the arm, the actual stiffness of each of the components was found using dial gauges in areas of interest (Figure 5), and then converting the measured linear motion into rotational deflection.

As the load was gradually increased, measurements were continually taken using the dial gauges. Upon reaching the maximum load it was gradually decreased back to zero. As expected the results were linear as shown in Figure 6. This test was repeated 3 times.

Using the measured stiffness values, the system was modeled as a 3rd order undamped oscillatory spring-mass system. The eigenvalues calculated from this model correlated well, within ±5%, with the results generated in the frequency response tests.

Static and Dynamic Testing. Static and dynamic tests were also performed using strain gauges. After manufacture of the major components and prior to assembly, each component was tested statically by applying the peak design loads predicted by dynamic modeling. Strain gauging was used to verify the predicted stresses and validate the FE model.

Test fixtures were designed and built to statically test each subassembly. The fixture to test the arm at 1 G above the design G-level is shown in Figure 7. The frame was attached to the end of the arm, at the roll axis, and to the pedestal. Loading was done by means of hydraulic jacks.

Another part of the arm test fixture was

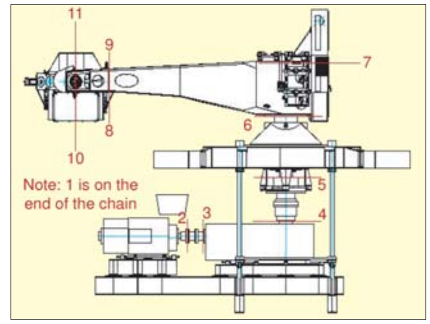

Figure 5. Test points in the stiffness test.

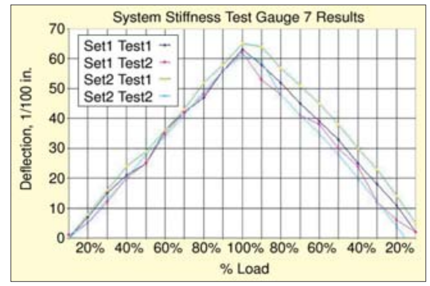

Figure 6. Deflection results for one of the test points.

made up of a triangular frame and horizontal struts. This frame was used to apply tangential loads to the centrifuge arm at the roll trunnions. A hydraulic jack was used at each lower end of the triangular frame to generate the desired tangential load.

After full assembly, the system was tested dynamically to verify the stresses predicted by FEA during the various load cases. A correlation between the predicted stresses and test results was performed.

Noise and Vibration Control. A Vibration Measuring System (VMS) was incorporated in the design of the centrifuge to monitor vibration signatures during the lifetime of the centrifuge. Accelerometers were attached to critical areas, such as the bearings in the pedestal and the gear reducer, and a data acquisition unit collects the output. These data were transferred to the VMS computer and the diagnostic software to predict possible failures before they become a real problem. The frequency spectrum was also analyzed for signatures of growing failures. These signatures depended on the specifications of the equipment, such as the number and type of gears, the type and number of rolling elements in a gearbox, and used as additional input to the VMS software.

A baseline signature was generated using a standard motion profile during factory testing and stored on the system hard drive. During the lifetime of the device, signatures from this standard motion profile will be monitored and compared with the baseline to find deviations and to generate a trend analysis.

Conclusions. During structural tests the predicted stiffness and bandwidth were evaluated and an extremely good match was found. Stresses were well

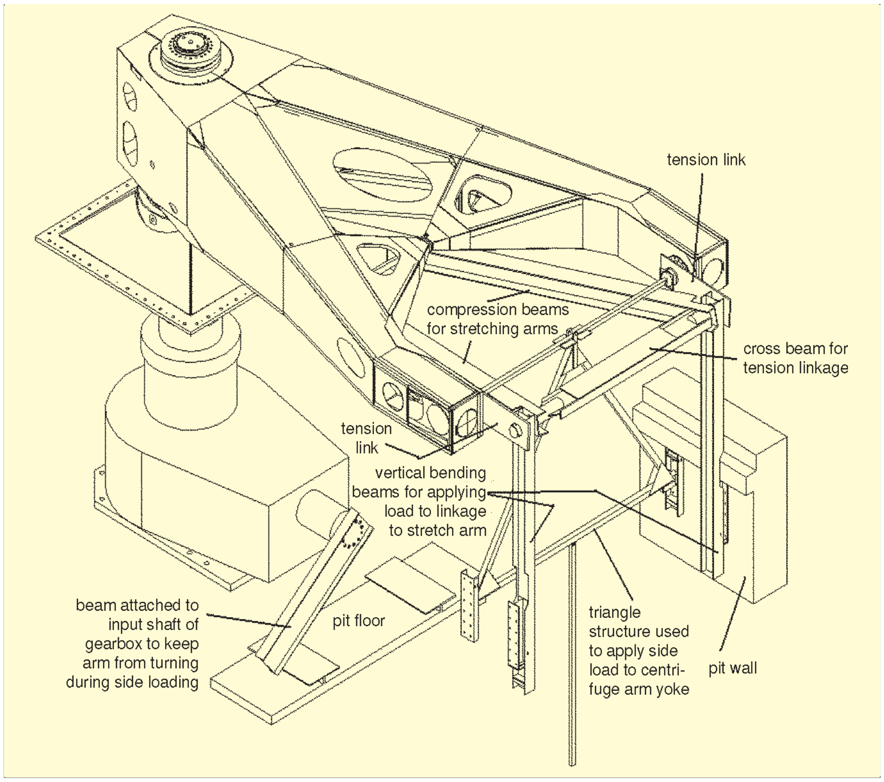

Figure 7. Arm yoke test fixture design.

within the predicted values. The three drive systems for the main and gimbal drives, selected long before the assembly of the unit, using the theoretical values of models, performed within their selected capabilities.

Thorough tests with the advanced control algorithms revealed the superior performance of the device. Due to the high bandwidth of the rotational system, controllability was superior to previous designs. The design team proved that using ETC's thorough analysis and design iteration process before metal is cut is the best approach to achieve the required performance of a dynamic device such as a Human Centrifuge for Authentic Tactical Flight Simulation.

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