DEVELOPMENT OF AN ADDITIVELY MANUFACTURED TURBINE BLADE TUNED MASS ABSORBER

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ABSTRACT

An innovative concept using a tuned mass absorber for resonant response reduction of turbine blades that is integrally fabricated into the blades using additive manufactured has been developed. Avoiding high resonant response and resulting high cycle fatigue failure is a major concern of the $100B worldwide turbine industry, which encompasses power generation, jet engines and rocket engine turbomachinery. Blade failure is potentially catastrophic, and although preventative measures using dampers do exist, these solutions are extremely expensive to develop and are not always effective. In addition, many of the existing techniques do not work for newer integrally bladed disks (or blisks), where there is no inherent damping in the assembly. The proposed concept, in which a tuned mass absorber re-arranges the structural dynamics and moves energy from the blade to the absorber, is designed specifically for blisks, and is intentionally linear, enabling accurate response prediction during design. Single blade prototypes have been analyzed, fabricated, and tested, and different absorber concepts have shown a reduction in response of up to 60%. After an extensive commercialization and prior art search, MSFC determined the innovation merited the generation and submission of a patent application in August ’21. Funding is now being sought to fabricate a 20-bladed blisk which would be spun at operational speeds with substantially higher and more realistic pressure loads in a special spin facility. Successful completion of this program would raise the TRL from 3/4 to 6/7, significantly improving the viability for adoption of the concept not only in rocket engines but other industrial applications as well.

INTRODUCTION

Turbines are used in a variety of applications, ranging from the power industry, where they are used to generate most of the power worldwide, to jet engines turbofans and rocket engine turbomachinery. Sales of all gas turbines are estimated to be approximately $80 billion/year.[1] A major problem for turbines is high resonant response of the blades, which can cause high cycle fatigue cracking and failure (fig. 1). It was estimated in the 90’s that this cost the industry approximately $100M/year.[2] Although research and development efforts have significantly reduced the failure rate, it still happens occasionally, and since it is a catastrophic and potentially dangerous event, expensive hardware mitigation techniques are an absolute requirement since off-nominal operation and wear in excitation hardware can cause unanticipated excitation frequencies (assuming the nominal operation itself does not encounter resonance, which isn’t always the case). In addition, the recent move away from separate inserted-bladed-disks (fig. 2) towards monolithic “integrally bladed-disks” (blisks), which reduces part count by an order of magnitude and the associated manufacturing and tracking costs, also eliminates damping at the blade/disk interface, exacerbating the problem. One of the primary methods for addressing this problem in inserted bladed-disks is via the implementation of separate small block-like parts placed between the platforms of adjacent blades. These blocks rub against the platform during high resonant response, thereby providing frictional damping and reducing the response. However, most blisk design precludes the use of these designs because there generally there aren’t separate platforms. Some concepts have been introduced that can be implemented on a blisk, but these exhibit the following problems: 1) the results depend on friction or impact, which are essentially nonlinear, analytically-intractable conditions, and so impossible to predict during design, so the success of the damper would have to be entirely based on realistic testing of an entire blisk, a very expensive and lengthy proposition; 2) implementation requires extremely tedious and time-consuming welding of external objects onto the blades, and these pieces only mitigate a single mode; 3) attached external dampers consist of a viscoelastic or elastomeric material, for which the damping characteristics are not only also difficult to predict but frequently cannot withstand the extreme environments of many turbomachinery configurations.

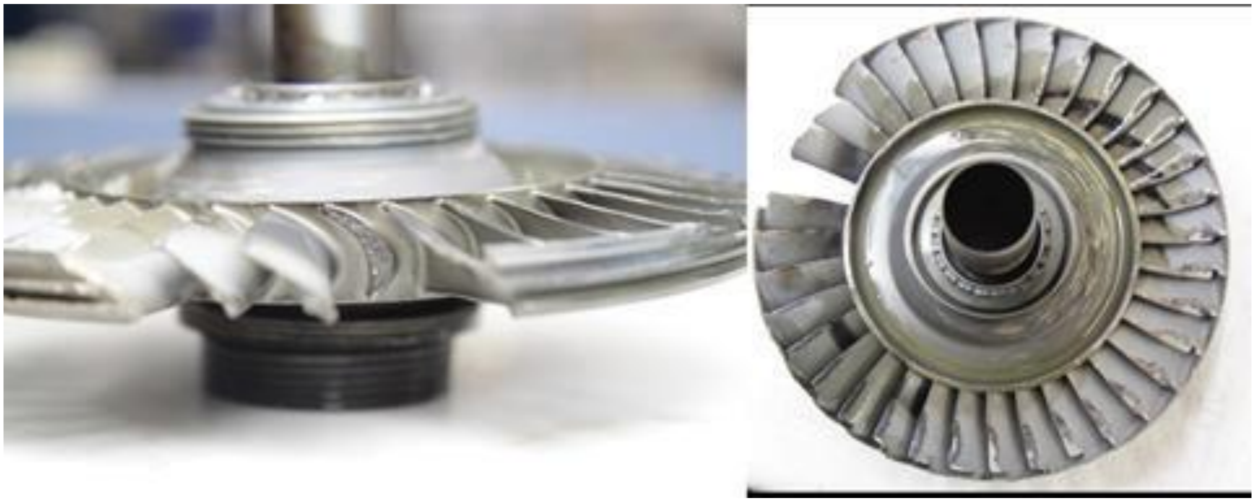

Figure 1. Blisk with blade failure

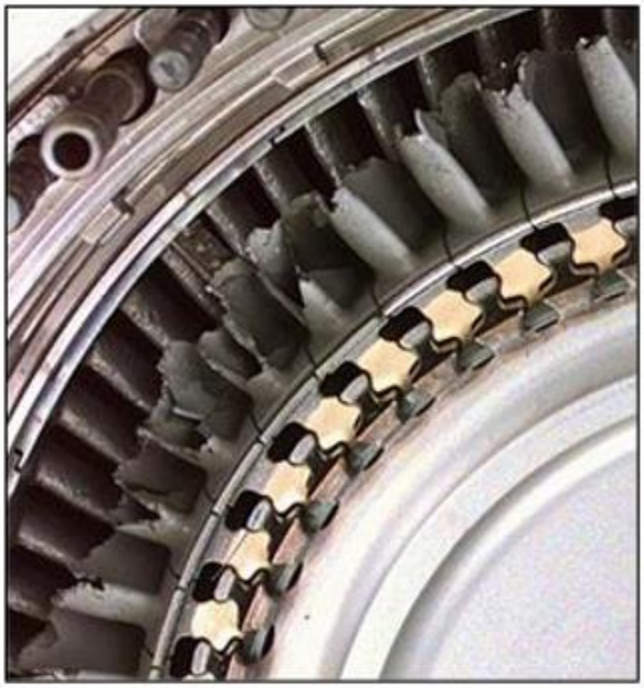

Figure 2. Inserted bladed-disk with blade failures

DEVELOPMENT OF NEW DESIGN

In 2018, additive manufacturing (AM) had advanced to the point where the design space of potential resonance-reducing mechanisms for turbine blades could be significantly expanded. This allowed the well-recognized principle of tuned-mass-absorption (TMA) to be applied to this problem and thereby could potentially avoid the pitfalls described above. This principal states that a small SDOF spring-mass system can be attached to a primary structure, and that if its natural frequency is equal to a natural frequency of the primary structure then it will bifurcate that single mode into two modes, each of which has a much-reduced response to a harmonic excitation than the original mode. A design was created that takes advantage of the capability of laser metal sintering (LMS), a form of additive manufacturing, to inexpensively fabricate a TMA shaped like a column completely inside the airfoil, thus eliminating the need for expensive welding that is the case with similar damper concepts. The TMA has an elliptical cross section that provides three parameters that can be optimized, allowing targeting of at least two modes in any frequency range, unlike other designs which can only dampen usually a single fundamental mode. In addition, the base of the TMA, which is the location where the energy is transferred from the blade, can be placed at the location in blade with a significant amount of response, unlike traditional under-platform or shroud dampers, which have an order of magnitude less modal response.

An initial single-blade prototype with the commonly used impulse, constant cross-section airfoil of roughly two square inches (fig. 3) connected to a roughly 3”x3”x3” block was designed, analyzed, and fabricated (fig. 4). The absorber for this first prototype was oriented along the spanwise axis. The TMA column intersection with the airfoil is filleted to reduce stress concentrations, and a small hole at the top of blade is also integrally fabricated for blowing out leftover powder from the LMS operation. A hole in the front is also built into the design for the prototypes to allow measurement of the TMA response by the laser vibrometer used in dynamic testing. Since the LMS metal powder layers are laid down and solidified for the prototypes in a direction consistent with how an entire blisk would be fabricated, i.e., transverse to the entire blisk, or parallel to the chord, this spanwise design was originally thought to require a support lattice structure during additive manufacturing, which would then have to be removed via the fabrication and use of an electromagnetic discharge machine (EDM) tool, an expensive, labor-intensive operation, especially for an entire blisk.

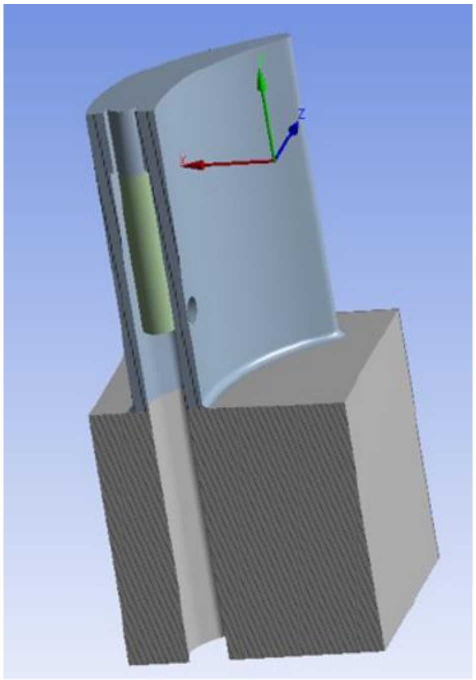

Figure 3. Cut-Away View of Spanwise Prototype

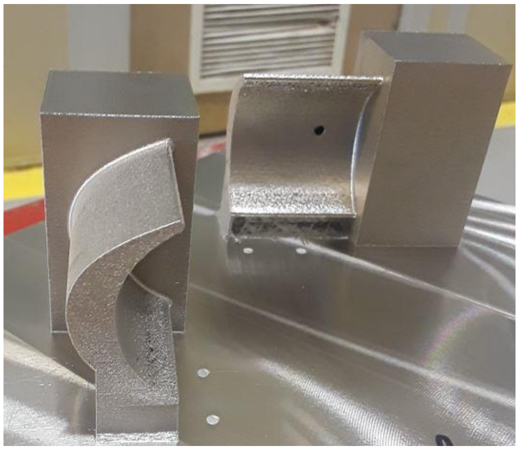

Figure 4. Fabrication of Spanwise TMA and Baseline Prototypes

The analytical optimization of the TMA is carried out within the ANSYS Workbench© software suite. The parameters used are the elliptical column's length, the major axis, and the minor axis, all which are constrained by the size of the cavity in the airfoil. This cavity size is a function of overall blade size, additive manufacturing minimum part separation requirements, and blade cross-section area strength requirements. The cavity/TMA clearance requirement of approximately 0.005" at present sets the minimum cross-section thickness at about 0.25".[3] The initial parameter settings are made by isolating the column analytically and optimizing such that the two fundamental modes of the column equal the two problematic modes of the blade modeled with the absorber cavity but without the absorber itself, which matches the theoretical TMA condition. The primary modes for the baseline blade at 7166 and 7370 Hz are shown in fig. 5. A mode shape of the resulting TMA design is shown in fig. 6, clearly showing how most of the motion is in the absorber rather than the blade.

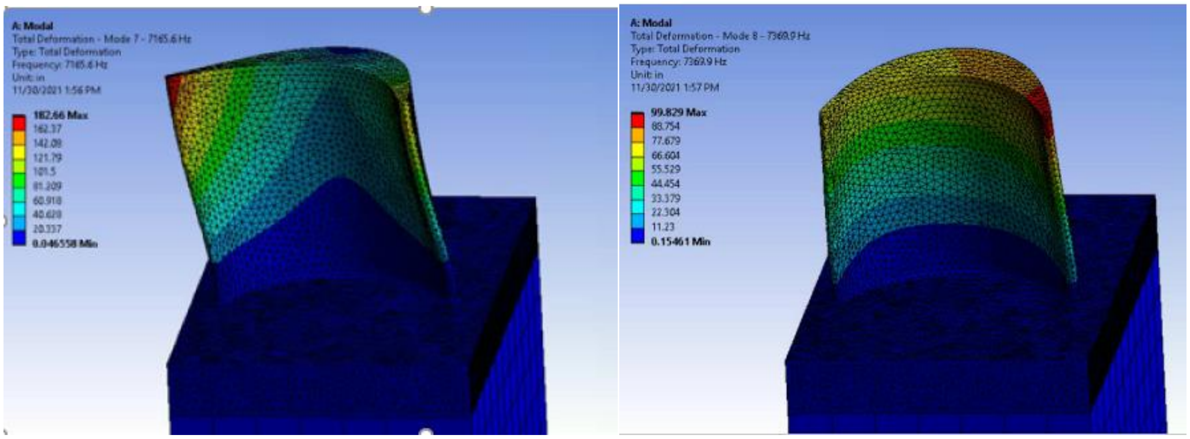

Figure 3. Fundamental Stiff-wise and Flex-wise Bending modes of Baseline blade

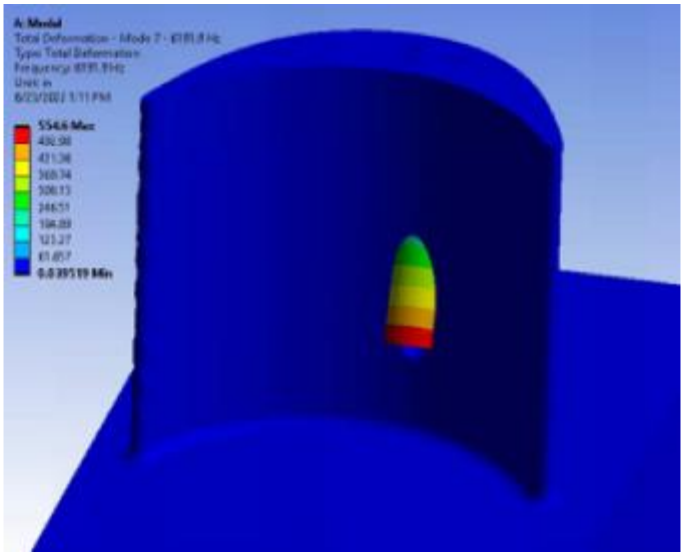

Figure 6. TMA mode (deformation greatly exaggerated)

This is not the final optimized solution, though, because a forcing function will favor one mode over another. Therefore, a common generic loading function, which was chosen to be a unit pressure load on a spanwise strip along the leading-edge pressure face, is applied, and the displacement of a single location on the tip of the blade is chosen as the response. This pressure field is chosen to excite both flex-wise and stiff-wise/torsion blade modes. A material damping value of 0.1% is assumed for the forced response analysis, which is typical for monolithic blisks. It is critical to note that this damping value will determine the amplitude of the response peaks for both the baseline and absorbed blades, but that the percentage of reduction of the absorbed blade should be independent of the material damping. The peak response of the peak responding location on the airfoil surface of the TMA blade is then minimized using standard optimization techniques provided in the software, resulting in final values for the TMA geometry parameters. Although implementation of the geometric optimization script is somewhat difficult (SpaceClaim is used here), it should be within the capabilities of most engineering organizations.

Both the baseline blade and the first prototype were then fabricated and finished according to additive manufacturing procedures. The modes are first obtained and then the frequency response measured. This first prototype was dynamically tested using a shaker, along with the baseline solid blade without an absorber. The response of nine locations on the pressure side and the TMA itself were measured using a laser doppler vibrometer. Although good results were obtained (reduction around 50%), several major errors in this setup were discovered eventually. First, the model was not optimized to the true as-fabricated prototype, and more importantly, what was thought to be the blade flex-wise bending mode was actually a shaker bending mode (they looked almost identical for the 9 measured locations on the airfoil). In addition, the cubical base of the blade was not sufficiently large to enable the blade to act independently. The results for this test are therefore considered unusable.

SECOND AND THIRD PROTOTYPES

To eliminate the lattice-support-removal problem, an absorber design consisting of a curved column parallel to the blade chord was designed and optimized and a prototype fabricated and tested (fig. 7). This orientation of the column allows it to be additively fabricated in the same direction as the rest of the blade and therefore it is self-supporting, so the expensive extra step of removing the absorber support lattice is not required.

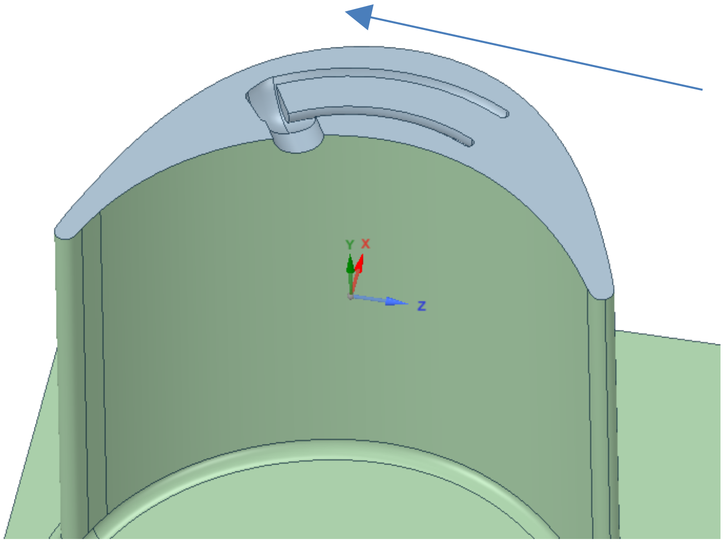

Figure 7. Chordwise TMA concept with direction of Additive Fabrication indicated by arrow

A second prototype using this chordwise concept was therefore designed, analyzed, optimized, fabricated, and tested. However, the shaker-mode interaction issue was discovered during testing, rendering the optimization incorrect, so a third prototype was designed and tested, applying all the lessons from the first two prototypes. The optimization analysis showed a 60% reduction in the response and the correct modal bifurcation of the two targeted modes into four, as shown in fig. 8a. This prototype was designed to minimize the response to an impact on the tip, as shown in fig. 8b, since that was now determined to be the best way to test the structure both to obtain the modes and the response reduction for that tip location.

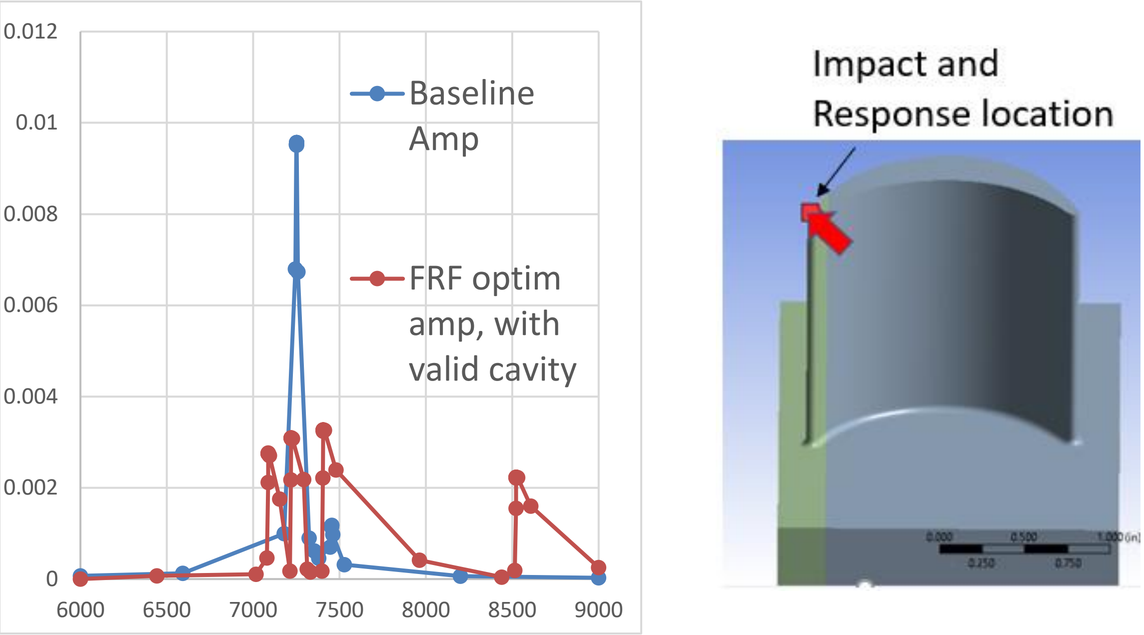

Figure 8a. Frequency response (FRF) of 3rd prototype to impact at location identified (8b)

A modal test was initially performed with this prototype, this time in a free-free configuration using an impact hammer, and the modes for both the baseline and TMA blades matched with excellent errors of between 0.3% to 1.9%. The test FRF magnitudes did not agree, though, with a reduction of only 30.5%, still excellent but in disagreement. The reason for this was not immediately apparent, as one of the advantages of this concept is that the response should be completely linear, so if the modes matched analysis, the FRF should as well. Upon further examination of the peaks, it was discovered that using the half-power method for determining damping, the TMA yielded ζ = .0156% while the baseline yielded .0284% (fig. 9). Although these values are tiny, they will drive the magnitude of the FRF, so this difference completely explains the discrepancy. As both the baseline and TMA blades were fabricated simultaneously, it has been hypothesized that since neither was heat-treated, they cooled at a different rate, probably due to the cavity in the TMA blade, causing the different damping values. Since the purpose of the test was to evaluate the efficacy of the TMA, which is independent of damping, a more

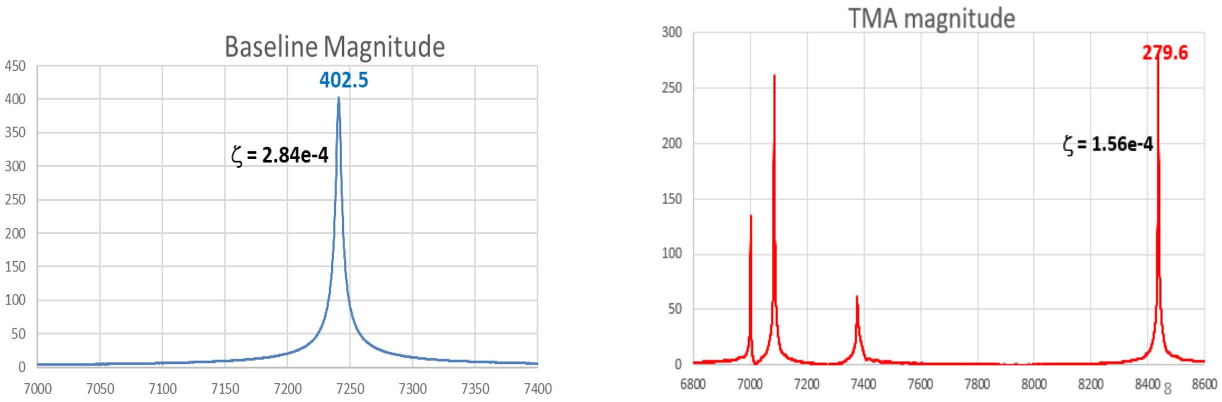

Figure 9. Prototype Baseline and TMA test FRF's with extracted damping

representative comparison is to therefore normalize the responses by the ratio of the two damping values. This yields a reduction of 62%, almost an exact match with the analytical prediction. In future fabrication, a heat-treatment step will be added to hopefully eliminate this discrepancy.

RETURN TO SPANWISE CONFIGURATION

One obvious problem with any of the TMA proposed designs is that by absorbing the energy of the blade mode, the response of the absorber itself potentially could be so large that it fails. In addition, the spin load on the TMA needs to be calculated. These two values were generated during the testing of the chord-wise TMA concept in prototype three, and while the resulting high dynamic stresses in the TMA (>100 ksi) can perhaps be accepted due to the fail-safe design and low probability of resonance, the equally high stress due to a spin rate of 25KRPM, not uncommon in rocket engines, is unacceptable. Simultaneously, very recent advances in additive manufacturing indicate that the expensive lattice support thought to be required for the span-wise concept are no longer necessary. A decision was made to return to this configuration, therefore. In this concept, the spin load is entirely compressive on the TMA, for which metals are significantly more capable, and in addition, the vibratory tensile stress on the TMA during resonance is essentially cancelled out by the compressive spin stress, essentially “killing two birds with one stone”. The buckling margin is also well within acceptable limits. Representative values of these stress values are presented in the next section.

BLISK ANALYSIS AND TEST PLAN

During discussions with potential users of this technology, it became apparent that the technology readiness level needed to be increased by testing a full-scale blisk in a specially designed spin rig that could apply realistic rotational speeds and somewhat realistic pressure loads. A proposal was made to and approved by NASA’s Center Innovation Fund for FY23 to fund this project, which is of course significantly more expensive than the previous prototype testing. The success of prototype three, even with the caveats, was critical in getting the funding as it showed the concept was practical. A blisk has been designed and optimized using the procedure described earlier, and the analytical FRF shows a reduction of 54.3% (fig. 10). Fig. 11 shows the excited mode shape of the TMA blisk, clearly exhibiting

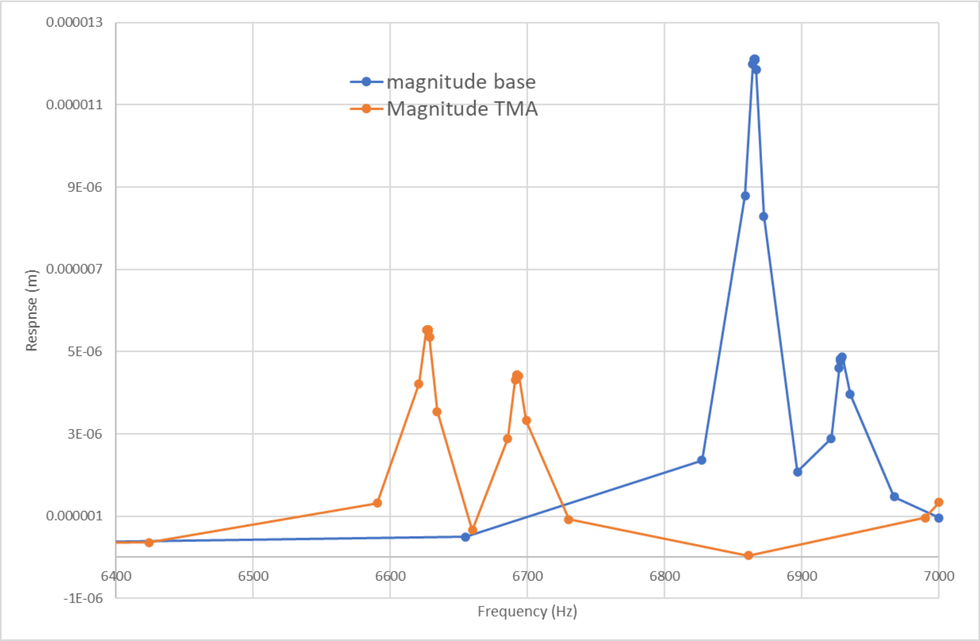

Figure 10. Analytical FRF comparing baseline blisk with TMA blisk

dominance of the TMA motion, and fig. 12 shows the stress field, with a maximum of under 5 ksi on the TMA due to the combined spin and resonant loading.

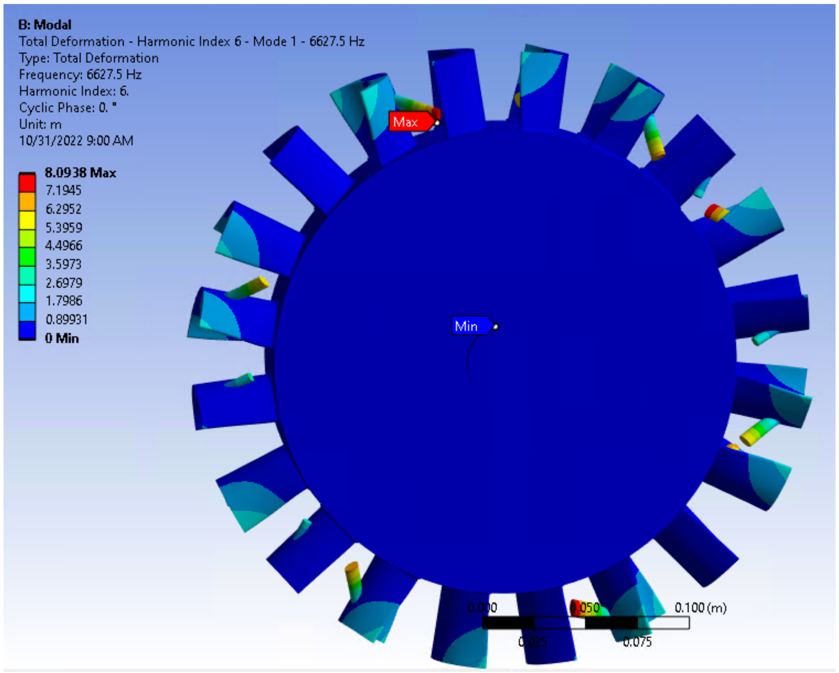

Figure 11. Blisk Nodal Diameter 6 mode (deformations greatly exaggerated)

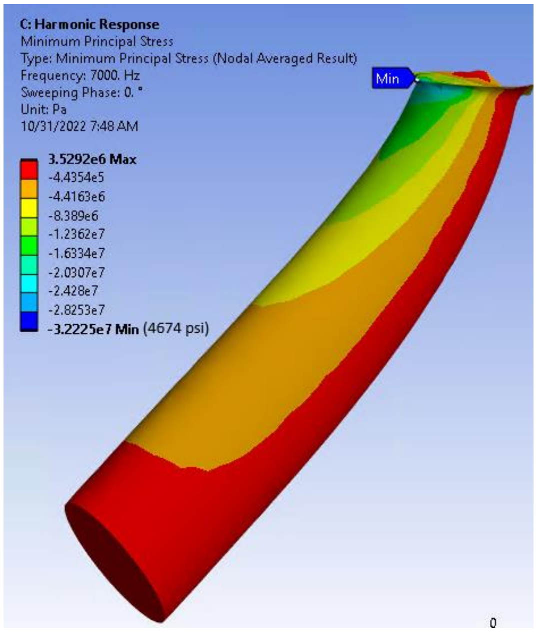

Figure 12. TMA stress field due to combined loading

The plan at present is not to proceed with this specific design, but to use an airfoil shape provided by an industrial partner which is more representative of their designs. After fabrication and heat-treatment, the blisk will be spin tested at the Ohio State Gas Turbine Laboratory, one of the few fully-capable spin-pit facilities in the United States.

SUMMARY AND CONCLUSIONS

An innovative yet straightforward technology has been developed at NASA/MSFC to address the resonant response of turbine blades. This technology, which a patent has been applied for, has the following benefits:

1) The TMA is very effective at reducing blade tip response, with analysis showing a 54% reduction for a typical blisk.
2) The design can be optimized for maximum energy transfer for specific modes, especially when compared with under-platform or shroud dampers.
3) The response is linear and therefore analytically tractable, unlike every design that uses traditional "damping" techniques, which are inherently nonlinear. This allows reliance on analysis rather than very expensive, dedicated damper spin-pit testing for each new turbine.
4) If AM is chosen for blisk fabrication, there is no additional cost for the implementation of the TMA.
5) The design of the TMA can be targeted at any two modes of concern.
6) The concept can be extended to other turbomachinery rotating and static components.
7) Directed Energy Deposition, a form of AM outside of a constrained box, enables scalability of the concept to large turbine blades.

One of the largest disadvantages at present is that the minimum thickness necessary to accommodate the cavity and TMA with sufficient clearance between the two is approximately 0.25", and many turbine blade do not reach this value. However, AM technology is advancing rapidly, and it is anticipated that this gap requirement will be reduced. Another concern is the reduced HCF capability of AM materials; this is being addressed by new post-fabrication surface treatments, which yield close-to-machined properties.

A representative full-scale blisk is presently being designed and funding has been allocated to fabricate it and a similar baseline blisk for testing in a dedicated turbine spin rig. This should raise the technology readiness level to a point where industry will feel comfortable adopting it into their hardware, thus enabling safer and more reliable operation of their turbines.

ACKNOWLEDGMENTS

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