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OXIDE/OXIDE CERAMIC MATRIX COMPOSITE (CMC) EXHAUST MIXER DEVELOPMENT IN THE NASA ENVIRONMENTALLY RESPONSIBLE AVIATION (ERA) PROJECT

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ABSTRACT

LibertyWorks®, a subsidiary of Rolls-Royce Corporation, first studied CMC (ceramic matrix composite) exhaust mixers for potential weight benefits in 2008. Oxide CMC potentially offered weight reduction, higher temperature capability, and the ability to fabricate complex-shapes for increased mixing and noise suppression.

In 2010, NASA was pursuing the reduction of NOx emissions, fuel burn, and noise from turbine engines in Phase I of the Environmentally Responsible Aviation (ERA) Project (within the Integrated Systems Research Program). ERA subtasks, including those focused on CMC components, were being formulated with the goal of maturing technology from *Proof of Concept Validation* (Technology Readiness Level 3 (TRL 3)) to *System/Subsystem or Prototype Demonstration in a Relevant Environment* (TRL 6).

In April 2010, the NASA Glenn Research Center (GRC) and Rolls-Royce (RR) jointly initiated a CMC Exhaust System Validation Program within the ERA Project, teaming on CMC exhaust mixers for subsonic jet engines. The initial objective was to fabricate and characterize the performance of a 0.25 scale low bypass exhaust system that was based on a RR advanced design, with a 16-lobe oxide/oxide CMC mixer and tail cone (center body). Support Services, LLC (Allendale, MI) and COI Ceramics, Inc. (COIC) supported the design of a mixer assembly that consisted of the following oxide/oxide CMC components mounted on separate metallic attachment flanges: a) a lobed mixer and outer fan shrouds, and b) a tail cone. TRL 4 (*Component/Subscale Component Validation in a Laboratory Environment*) was achieved in a cost-effective manner through subscale rig validation of the aerodynamic and acoustic performance via testing at ASE FluiDyne (Plymouth, MN) and at NASA GRC, respectively. This encouraged the NASA/ RR/COIC team to move to the next phase of component development; full scale CMC mixer design for a RR AE3007 engine. COIC fabricated the full scale CMC mixer, which was vibration tested at GRC under conditions simulating the structural and dynamic environment of a mixer. Air Force Research Laboratory (AFRL, Wright-Patterson Air Force Base (WPAFB)) provided test support by assisting with instrumentation and performing 3D laser vibrometry to identify the mixer mode shapes and modal frequencies over the engine operating range.

Successful vibration testing demonstrated COIC's new process for fabricating full scale CMC mixers and the durability of the

Oxide CMC component at both room and elevated temperatures. A TRL≈5 (*Component Validation in a Relevant Environment*) was attained and the CMC mixer was cleared for ground testing on a Rolls-Royce AE3007 engine for performance evaluation to achieve TRL 6.

INTRODUCTION

Small turbofan engines, which are utilized on both regional transport and business jets, often have a mixed flow exhaust system featuring an exhaust lobed mixer (Figure 1) where the bypass (cold) air is mixed with the core (hot) exhaust gases (Figure 2) before exhausting to atmospheric pressure through a common propelling nozzle. Lobed mixers enhance temperature mixing of the two streams, and reduce average exhaust velocities and temperature [1]. As a result, the mixer exhaust nozzle provides a reduction in jet-noise [2]. The mixing process also increases gross thrust and improves specific fuel consumption (SFC).

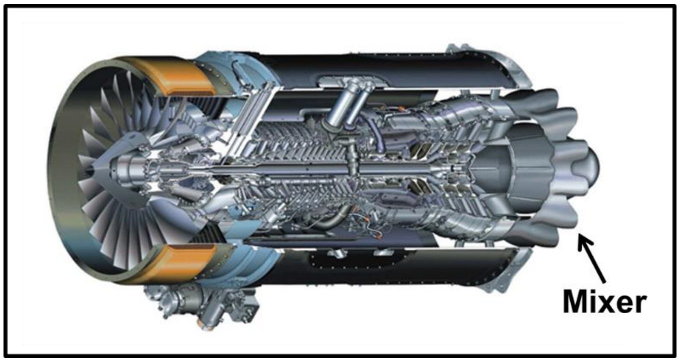


Figure 1: Example of an aircraft engine (RR AE3007) that has an exhaust mixer

Rolls-Royce has significant experience with designing turbofan engine exhaust mixers of varying complexity for jet-noise reduction or performance enhancement, or both. Lobed or forced mixers have hot and cold chutes that are radially-intertwined, to force the engine bypass airstream and the hot turbine exit exhaust gas stream to mix along the shear layer formed at the mixing plane (Figure 2) in both radial and circumferential directions. Forced mixers, when properly designed, can have a high mixing efficiency, which is a ratio of the actual thrust gain due to mixing to that of the ideal case [3]. Mixers need to be structurally stiff in order to maintain the desired profile for high mixing efficiency.

Metallic mixers, which are typically made of titanium or nickel based sheet metal, can be heavy and costly. Thin sheet metal mixer walls that may deflect and distort out of shape under thermal and structural loads must be stiffened. Oxide fiber reinforced oxide matrix (Ox/Ox) composite mixers offer an advantage as they are able to maintain their shape during engine operation. This would improve or at least maintain the desired mixing efficiency, and reduce fuel burn and jet noise. CMC mixers can increase component durability with higher thermal margin, and they offer enhanced ability to fabricate complex-shaped structures. While Ox/Ox mixers could retrofit or replace existing metallic mixers, RR felt the most attractive applications of the Ox/Ox mixers would be in future engine projects where the engines have higher combustor temperatures and the available metallic materials could not be used due to the high cost and the need for component cooling.

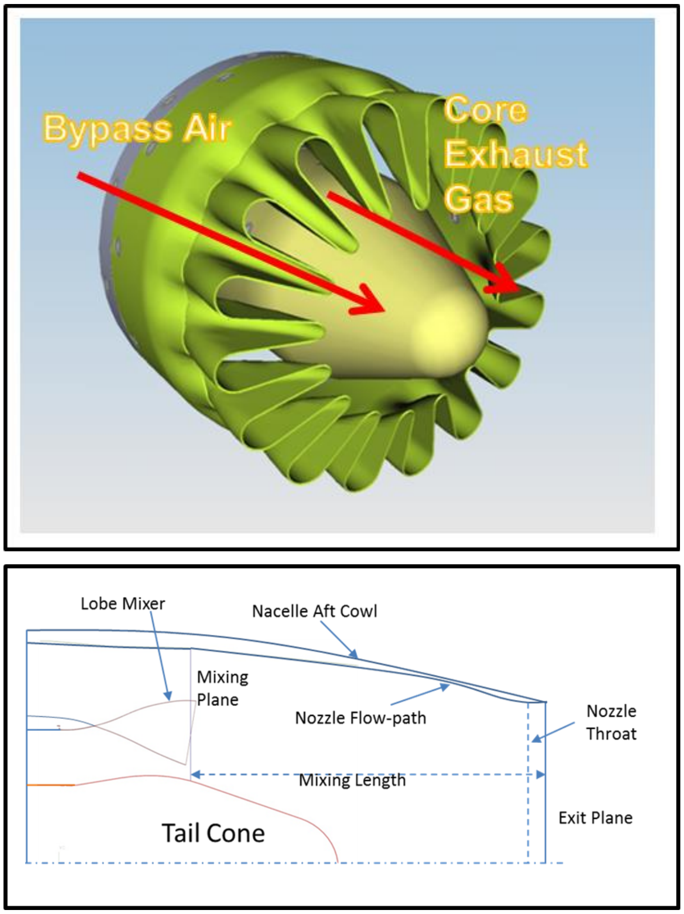


Figure 2: Diagram and schematic of a mixed flow exhaust system with lobed mixer

In 2010, NASA was pursuing the reduction of NOx emissions, fuel burn, and noise from turbine engines in Phase I of the Environmentally Responsible Aviation (ERA) Project (within the Integrated Systems Research Program) [4,5]. ERA subtasks, including those focused on CMC components [6], were being formulated with the goal of maturing technology from *Proof of Concept Validation* (Technology Readiness Level 3 (TRL 3)) to *System/Subsystem or Prototype Demonstration in a Relevant Environment* (TRL 6). The goal was to achieve TRL 6 for specific technologies by the end of 2015, in order to allow implementation of the technology by 2020.

In April 2010, NASA GRC and Rolls-Royce jointly initiated a CMC Validation Program within the ERA Project, teaming to develop an Ox/Ox exhaust system for aircraft engines. The Ox/Ox composites have been under development for decades and have only recently been matured for commercial aircraft applications [7-12]. Under Space Act Agreements (SAA), both organizations provided roughly equivalent amounts of funding. COIC was selected as our component manufacturing team member based on their experience with Ox/Ox composites and components. COIC had a significant material properties database for several Ox/Ox systems, and had previously fabricated some large (≈16” diameter) demonstration mixers. AS-N610™ Ox/Ox composite [13] was selected as the material system for the full scale CMC mixer because it is lightweight (density ≈2.83 g/cc), has excellent fatigue properties, is chemically inert and stable in an exhaust environment, and it has reasonably high strength and stiffness. The AS-N610 ™ CMC consists of an aluminosilicate matrix reinforced with relatively-inexpensive Ox fabric (woven Nextel™ 610 fibers). Compared to non-oxide CMCs, the AS-N610™ system is low cost and does not require a protective surface coating to prevent matrix or fiber environmental degradation.

Our starting Technology Readiness Level was TRL 3, based on COIC’s previous CMC mixer fabrication demonstration and their derived property database, and RR experience testing subscale conventional metallic mixers at different test facilities. NASA agreed with RR that successfully designing, fabricating, and characterizing the thrust and acoustic performance of a roughly quarter-scale 16-lobe Ox/Ox CMC mixer and center body for a conventional low bypass exhaust nozzle was the logical approach to achieving TRL 4 (*Component/Subscale Component Validation in a Laboratory Environment*).

1. SUBSCALE OXIDE/OXIDE CMC HARDWARE (MIXER, OUTER SHROUDS, AND CENTER BODY) AND METALLIC ATTACHMENT RINGS

Our goal in this phase of the subtask was to design and fabricate quarter-scale test hardware, including a 16-lobe Ox/Ox mixer and tail cone, a conventional low bypass exhaust nozzle, and fan and core flow adapters. The 16-lobe mixer has 16 outward pointing lobes. It also has 16 inward pointing lobes (Figure 3). The assembly includes Ox/Ox outer shrouds (fan flow fairings). Additional test hardware included attachment rings; one for the tail cone and one for the mixer and shrouds.

1.1 Design

The overall dimensions of the subscale component hardware were dictated by the ASE FluiDyne test rig that the team had selected for validation testing. This rig has often been used by RR. Support Services, LLC and COIC supported an in-depth design and analysis effort, while ASE FluiDyne provided the design of the adaptor hardware required to install the CMC test components. Thermal/structural finite element analysis (FEA) was conducted, utilizing CMC thermal/mechanical properties provided by COIC and boundary conditions provided by RR-based on realistic engine operating temperatures. The design iterations included the design of stainless steel (SS) attachment rings for connecting the mixer (and outer shrouds) and the tail cone to the test rig hardware. Resonance/natural frequency analysis performed on the mixer predicted the first 10 natural frequencies and mode (deformation) shapes. After a RR-led design review concluded that the analysis adequately simulated realistic operating conditions and that stresses in the subscale Ox/Ox components from thermal and structural loads had been reduced to acceptable levels, two sets of CMC hardware were fabricated by COIC and delivered to GRC.

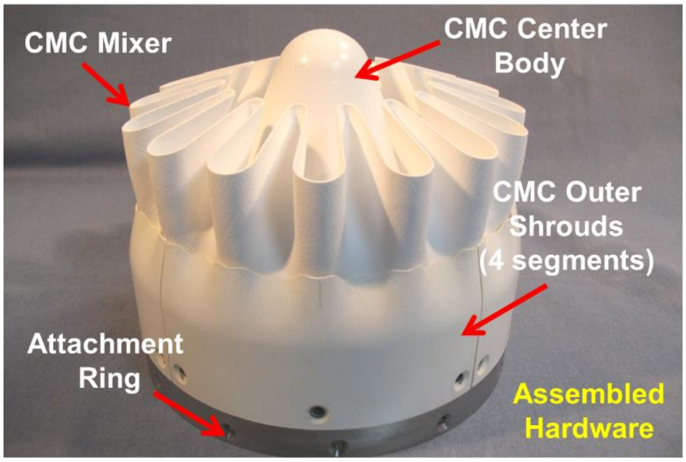


Figure 3: Subscale oxide/oxide CMC mixer and center body

1.2 Fabrication and Inspection of the Test Articles

A flow chart showing the COIC fabrication process for manufacturing Ox/Ox components is provided on the COIC website [14]. The thickness of the CMC articles (at any location) is dependent on the number of fabric plies present. The NASA/RR/COIC team had initially discussed fabricating and testing a mixer assembly that was ≈12” in diameter. However, this required larger dual flow charging stations and adaptors, and an expensive test facility that was well beyond the available budget. The scale of mixer hardware (roughly 0.25 scale, with 8” mixer diameter) was based on the capabilities of the selected test facilities. Based on relevant test experience, ASE FluiDyne (Plymouth, MN) and NASA GRC’s Aero-Acoustic Propulsion Laboratory (AAPL) were ultimately selected for evaluating the subscale aero-acoustic performance.

Fabrication of a small 16-lobe Ox/Ox mixer was a challenge. The team opted to fabricate the mixer and tail cone with Nextel™ 312 fiber reinforcement (woven fabric). The tensile moduli of Nextel™ 312 and Nextel™ 610 oxide fibers are 150 and 380 GPa, respectively [15]. Thus, the Nextel™ 312 fabric is more pliable/drapable, and it was better suited for making the small, subscale mixer and center body. The outer shrouds (four per set) were reinforced with Nextel^{TM} 610 fabric. The use of these two different fiber reinforced Ox/Ox CMCs in the subscale components was taken into account during the design process. Support Services, LLC was tasked to complete the design and structural analysis of the Stainless Steel (SS) attachment rings, which were subsequently manufactured by a machining shop in Michigan. ASE FluiDyne manufactured the remaining adaptor test hardware; the exhaust nozzle adapter, core and fan flow supply interface pipes, and a spacer for the tail cone. Close tolerances were required at various locations for each of the items, to assure proper fit under all test conditions.

COIC manufactured two sets of CMC test hardware. Based on visual inspection, the best mixer, fan shrouds, and center body were selected for testing. The CMC articles that were chosen for testing had very good surface finishes on the "tooled" side. Nondestructive evaluation (NDE) of the as-fabricated mixer and shrouds, which were attached to the same attachment ring, was performed using X-ray computed tomography at GRC (Figure 4). Software was used to obtain virtual slices (cross section views) of the hardware, allowing thorough inspection of the Ox/Ox parts for defects/delaminations. No significant defects were detected.

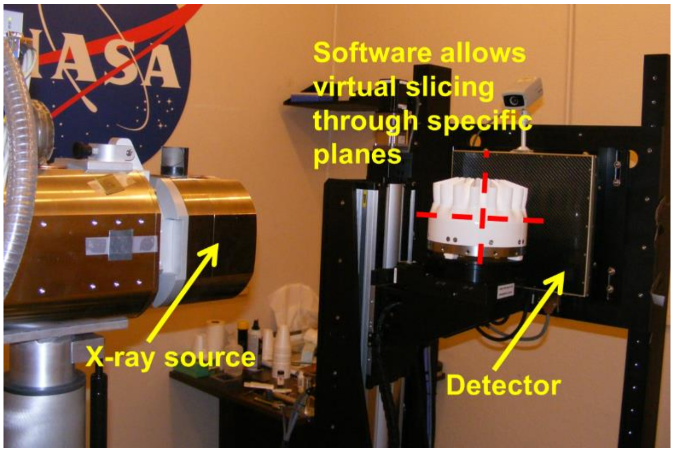


Figure 4: Nondestructive evaluation of the subscale Ox/Ox CMC mixer and outer shrouds assembly via X-ray computed tomography

1.3 Aerodynamic and Acoustic Testing

The exhaust mixer assembly (consisting of the CMC mixer and outer fan shrouds mounted on a metallic attachment ring, and the center body mounted on another metallic ring) was sent to ASE FluiDyne to assess its aerodynamic performance in the Channel 11 Hot/Cold Dual Stream Static Nozzle Test Facility. The dual flow rig uses a combination of hot and cold air flow streams to simulate mixer operating conditions (core exhaust gas and bypass air), thus, subjecting the mixer to through-thickness thermal gradients. The test matrix was based on previous RR experience with subscale mixer testing at FluiDyne, and it included various combinations of temperature and pressure ratios. RR used standard nozzle data reduction methods from FluiDyne to evaluate CMC nozzle performance. The fan pressure ratio, which is defined as the ratio of the upstream total pressure to exit atmospheric pressure, was varied from 1.4 to 3.0. The test matrix called for six "cold flow" and twelve "hot flow" tests; the "cold flow" test refers to unheated core and fan air flows (temperature ratio of 1.0). In both hot and cold flow tests, the total pressure of the core and fan (or bypass) streams was identical. In hot flow testing, a maximum temperature ratio (core flow to fan bypass flow temperature, in degree R) of 2.5 was evaluated. NASA and RR personnel visited FluiDyne to view the test-setup and monitor the nozzle testing. Figure 5 shows the Ox/Ox mixer assembly mounted in the Channel 11 Test Rig (shown with the metallic nozzle cowl removed). In this testing, the maximum core gas temperature was approximately 872°F (467°C). After completion of the testing, nozzle calibrations were performed to validate the performance data accuracy. Analysis of the nozzle test data indicated that excellent mixing efficiency was obtained. The CMC mixer geometry was a major factor contributing to the improved mixing performance, although other factors have also been identified.

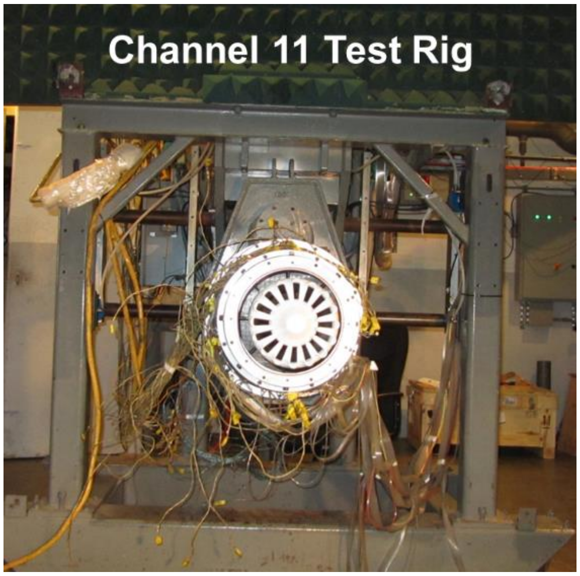


Figure 5. Performance testing of the subscale Ox/Ox exhaust mixer at ASE FluiDyne. View with metallic nozzle cowl removed

Next, the acoustic performance of the Ox/Ox mixer/nozzle was assessed at GRC using the Nozzle Acoustics Test Rig (NATR) in the AAPL (Figure 6). The AAPL is a large (65-ft radius), geodesic hemispherical dome-shaped facility that is lined with anechoic wedges on all chamber surfaces, including the floor, to prevent noise contamination during far-field sound measurements. A far-field microphone array suspended above the NATR (Figure 7) measures the noise distribution to characterize the sound produced by a nozzle exhaust system during testing. The mixer assembly and the nozzle cowl were mounted in the High

Flow Jet Exit Rig (HFJER) since it employs test interface hardware identical to that of the FluiDyne Channel 11 Rig. The HFJER is also a dual flow facility which uses a combination of hot and cold air streams to simulate a jet engine with a mixer operating with hot core exhaust gas and cooler bypass air. RR defined the test matrix based on their previous AAPL testing of subscale metallic mixers. AAPL, due to its higher temperature capability, allowed the CMC mixer hardware to be tested at a higher temperature ratio. Thus, a maximum core gas temperature of approximately 1020°F (549°C) was achieved. Analysis of the data that was obtained indicated that as expected the Ox/Ox mixer assembly did provide an enhanced level of noise reduction. The data could not be directly compared to a reference metallic mixer previously tested at AAPL because of bypass ratio mismatch. However, that outcome was acceptable and consistent when data was corrected for equivalent nozzle flows. The acoustic performance of the CMC mixer/nozzle and that of an equivalent metallic exhaust system, therefore, would be similar. Another acoustic testing accomplishment was that the CMC hardware was subjected to 5+ hours of endurance testing at high temperature. Interim and post-test inspections indicated that the Ox/Ox CMC articles did not incur noticeable damage.

Figure 6: GRC Aero-Acoustic Propulsion Laboratory

1.4 TRL 4 Achieved

Periodic visual inspections during performance tests and NDE following the completion of endurance tests did not detect any damage to the subscale Ox/Ox hardware resulting from those tests. Overall, the demonstration of COIC's ability to fabricate a high quality, complex subscale Ox/Ox component and the successful completion of the aerodynamic performance testing resulted in TRL 4. This achievement encouraged the NASA/RR/COIC team to move forward with plans to build and test an AE3007-size full-scale Ox/Ox mixer.

Figure 7: Nozzle Acoustics Test Rig, with CMC hardware mounted

2. FULL SCALE OXIDE/OXIDE CMC MIXER AND ATTACHMENT FLANGE

The main objectives were to 1) minimize thermal/mechanical stresses in a full scale CMC mixer and a compatible attachment flange through in-depth design and analysis, 2) evaluate the manufacturability of the large, complex-shaped component, 3) characterize the modal frequencies and mode shapes, and compare experimental results with predictions, and 4) assess load characteristics of an Ox/Ox mixer under simulated hot engine environment. This was done by conducting vibration tests at both room temperature and 700°F (371°C). A successful vibration test of a full scale engine component enables a TRL≈5, and demonstrates durability of a similarly-manufactured component for a TRL 6 engine test. Initial plans included the fabrication of a second full scale mixer for the Rolls-Royce AE3007 engine test.

As described in the following sections, two full scale Ox/Ox mixers were designed, fabricated, and vibration tested. The first mixer failed in 2013 during vibration testing due to a processing defect which resulted in crack formation and growth. After the team considered the "Lessons Learned" from the test data, the design was slightly modified, and an alternate processing approach was used to fabricate a second mixer in 2014 that survived over 2 million cycles of vibration testing at GRC. At that point, the RR/NASA/COIC team decided that the mixer had demonstrated the structural integrity required for ground-based engine testing, as it did not exhibit any structural damage from the vibration testing.

2.1 Design—CMC Mixer 2013

The design effort for the first full scale CMC mixer assembly (referred to as CMC Mixer 2013) built upon the previous design and analysis of the subscale 16 lobe Ox/Ox mixer. The main differences in this study were that the maximum diameter of the full-scale component is approximately 30" and the mixer configuration and attachment ring are significantly different. A different metal (IN718) was selected to make the attachment ring (flange), to be consistent with the existing attachment flange used in the AE3007 production mixer. The flange was designed to allow the mixer to be mounted to an AE3007 engine via attachment to the Rear Turbine Bearing Support with 8 axial bolts. Support Services, LLC and COIC supported an in-depth design and analysis effort to minimize component weight and thermal/mechanical stresses, with consideration also given to fabrication issues. Thermal/structural finite element analysis (FEA) was conducted with CMC thermal/mechanical properties for AS-N610 ™ (provided by COIC) and RR-defined boundary condition data (operating conditions that a mixer for a turbofan engine would experience). A standard ply lay-up throughout the component was assumed. RR ensured that the modeling yielded realistic component surface temperatures. Design changes were implemented to reduce local stresses. Additional analysis was performed to assess the retention of shape during operation, taking into account material stiffness (modulus of elasticity) and CTE. It was determined that the CMC mixer should exhibit significantly less distortion than an AE3007 metallic mixer with the same 16 lobe mixer design, which should lead to improved performance.

Resonance/natural frequency analysis was performed on the mixer/flange assembly, and the natural frequencies and mode (deformation) shapes occurring between 30 - 350 Hz were predicted (Figure 8). Each of the identified mode shapes was examined to determine which frequencies are of greatest concern. Component fabrication considerations were discussed during the design phase, to avoid developing a configuration that would present significant processing problems. After a RR-led design review concluded that the analyses adequately simulated realistic operating conditions and that stresses in the full scale mixer had been reduced to acceptable levels, RR issued a CAD (computer aided design) model and drawings that suggested component tolerances.

2.2 Fabrication and Inspection of CMC Mixer 2013

The CAD model was used to create a stereolithography model that COIC used to make a mold (tool) for laying-up the mixer. This mold was critical, because it influenced COIC's ability to control the dimensional tolerance of the full scale component. A flow chart showing the typical fabrication process used by COIC to manufacture Ox/Ox composite components is provided on the COIC website [14]. Following the lay-up of pre-pregged plies, curing, and tool removal, the mixer was sintered (high temperature heat treatment) to strengthen the matrix of the composite and then machined to trim the edges of the lobes and base, and to incorporate bolt holes (related to the attachment ring). The mixer was attached to the metallic flange (at COIC) that was provided by RR. COIC performed a detailed visual and "tap" inspection of the mixer and documented (via notes and photographs) any defects that were observed. Various minor defects were detected; some of which could be repaired. In addition, some large circumferential, through-thickness wrinkle defects were observed in the area beneath the mixer lobes, and some asymmetrical features were noted.

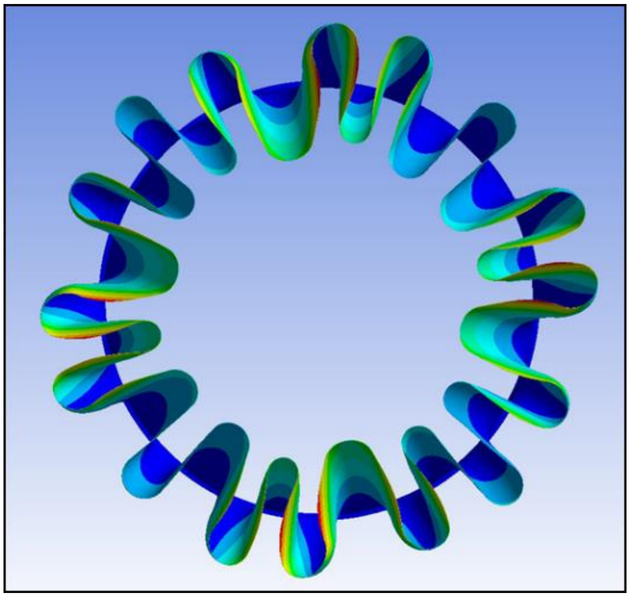


Figure 8: Example of a predicted mode shape showing non-uniform distortion of the lobes at a natural frequency

After a visual inspection at GRC the mixer was taken to LibertyWorks® in Indianapolis, IN, where a white light geometric inspection [16] was performed. This procedure yielded a model/representation of the complicated shape, which was compared with the CAD model of the article. This allowed the team to assess conformity to the specified dimensions, and it indicated the ability of COIC to fabricate the component using basic tooling that hadn't been optimized. The team discussed the defects noted by COIC and any geometrical deviations from design that were detected with the white light inspection.

2.3 Design, Fabrication, and Inspection of CMC Mixer 2014

As discussed in the following section on Vibration Testing, CMC Mixer 2013 did not have sufficient structural integrity to survive and complete the vibration test matrix. A crack formed in one of the through-thickness circumferential wrinkle defects that had been observed, and it ended up propagating along that defect until it was about 10" long, and testing was discontinued. However, no other cracking was detected, which indicated that a CMC mixer that did not exhibit such processing flaws could "survive" the remaining test matrix. The team discussed the fabrication of a second mixer with the objective of eliminating large wrinkle defects, as well as building upon the previous effort to improve tolerance, surface finish, eccentricity, and uniformity of the mixer lobes. COIC subsequently conducted various in-house studies to identify improved processing approaches for fabricating a second CMC mixer that could also be used for engine testing following vibration testing.

The processing of the second mixer (CMC Mixer 2014) yielded a component that was clearly superior to CMC Mixer 2013. Figure 9 shows the mixer prior to the machining of the holes for the attachment ring bolts. GRC received the second full scale Ox/Ox mixer in May, 2014. That component was more symmetrical and fit better within the attachment flange than Mixer 2013 had, and it did not have any large, through-thickness wrinkle defects. Some small wrinkles were present on the outer surface, and other minor defects were noted. This component did not undergo a white light inspection.

2.4 Testing the Full Scale CMC Mixers: Test Set-Up, Laser Vibrometry, Instrumentation, and Vibration Testing

The natural frequencies of both full scale CMC mixers were examined with 3D laser vibrometry to characterize their mode shapes. A small impact hammer was used to excite the modes over a specified range of frequencies [17]. Then, the mixers were instrumented with high temperature dynamic strain gages and vibration tested at GRC under conditions simulating the structural and dynamic environment encountered during AE3007 engine operation. Lessons were learned from the testing of CMC Mixer 2013, which led to modifications in the instrumentation of CMC Mixer 2014. While the focus of the following sections is on CMC Mixer 2014, information on CMC Mixer 2013 is also presented.

Figure 9: CMC Mixer 2014 prior to machining of holes

RR prepared the initial vibration test matrix based on their knowledge of mixer operating conditions and their experience with vibration testing of baseline metallic mixers. The testing included both room and elevated temperature testing to 700°F (371°C). Elevated temperature testing was of interest due to the need to assess the stresses induced by the CTE (coefficient of thermal expansion) mismatch between the attachment ring and the Ox/Ox mixer.

2.4.1 Vibration Test Set-Up

The vibration testing of the mixer was conducted in the GRC Structural Dynamics Laboratory (SDL). The SDL provides excitation, control, and data acquisition and processing capabilities. Each mixer was attached to a circular metallic mount plate that had been bolted onto a large shaker table slip plate. The mixer mount plate, which was designed and furnished by RR, was needed since the attachment ring could not be bolted directly to the slip plate. A high temperature insulating millboard (HTM) panel was sandwiched between the slip plate and the mount plate, to serve as a thermal barrier and minimize heat flow into the slip plate during hot testing (Figure 10). This was necessary to keep the lubricating oil beneath the shaker slip plate from overheating. This millboard remained in place throughout the vibration testing so that results obtained from testing at different temperatures could be directly compared. Steel panels were used to effectively form a frame that helped hold the millboard in place.

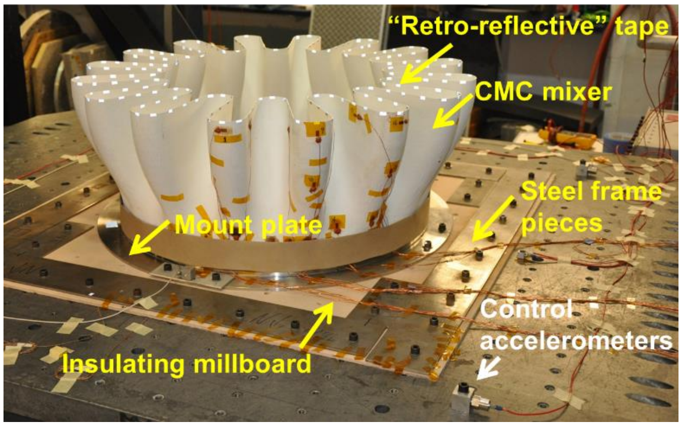


Figure 10: Full Scale Test Set Up - Ox/Ox CMC Mixer 2014 mounted on slip plate in the GRC Structural Dynamics Lab

2.4.2 Use of 3D Laser Vibrometry to Characterize Mode Frequencies/Shapes

The objective of the modal testing was to determine and characterize the natural frequencies of the Ox/Ox mixer from 10 - 350 Hz experimentally. The test data was compared to the pre-test predictions calculated from the ANSYS finite element model (FEM). The data was then used to determine the primary frequencies at which to conduct the room and high temperature fatigue (dwell) tests, where the mixer would be subjected to selected stress levels to assess its durability. The experimental method used to determine all modal parameters was based on characterization using a three-dimensional (3D) scanning laser

Doppler vibrometer system. The vibrometer system used for the modal testing was the Polytec PSV-500-3D (Irvine, CA). This system is able to measure both in-plane and out-of-plane motion of complex parts using three separate scanning vibrometer sensor heads. The sensor heads serve as laser sources, cameras, and detectors. Three measurements are made simultaneously from three different directions. From the known CMC mixer geometry, local x, y, and z velocity components on the mixer were calculated from the angles of incidence of the laser beams from the three sensor heads.

The first modal tests were conducted in April of 2013 in the GRC SDL on CMC Mixer 2013. The Ox/Ox mixer/metallic attachment ring assembly was bolted to the mount plate, which was bolted to the slip table (with the HTM between the mount and slip plates). The same boundary condition of the test article was maintained throughout the modal survey and vibration testing. Due to schedule constraints and the need for time-efficient modal testing, the top rim of the mixer (trailing edge of the lobes) was selected for acquiring response data. The pre-test FEM prediction showed that all of the mode shapes of interest (out of all of the symmetrical and non-symmetrical modal frequencies) could be captured by utilizing about two hundred measurement points along the narrow rim (trailing edge) of the mixer. The nominal thickness of the rim was approximately 60 mils (1.5 millimeters). A minimum of twelve measurement points were established per lobe, by marking those locations on the edge of each lobe with small pieces of retro-reflective tape (Figure 10). The retro-reflective tape was used to scatter laser light to improve the quality of the return signal to the Doppler detector in each laser head. The scanning laser heads (sensors) were positioned on bridge platforms overlooking the vibration table, as shown in Figure 11.

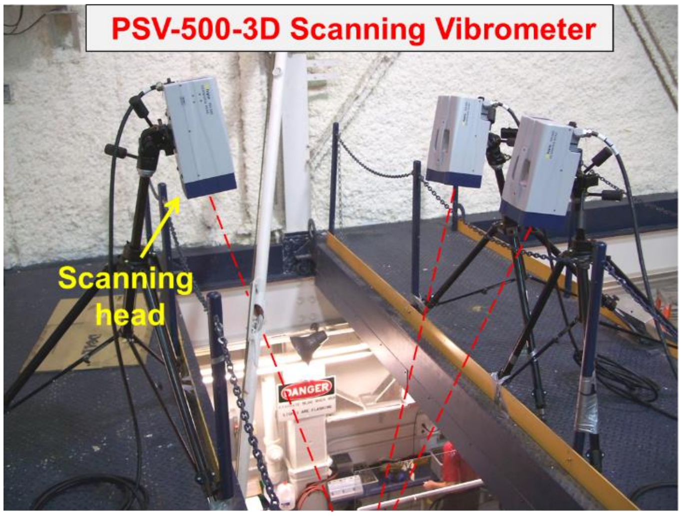


Figure 11: Scanning vibrometer sensor heads positioned above CMC Mixer 2013 during room temperature characterization of mode frequencies and shapes at GRC

During the experimental modal testing several different excitation methods were successfully used to characterize the basic structural response of the CMC mixer assembly. Three different techniques (acoustic horns/drivers, a small impact hammer, and the SDL shaker table (with displacement perpendicular to the mixer centerline—under a low level flat random condition of 0.25 g_{rms}, 30 – 2000 Hz)) were used to excite the modes. Each approach provided similar results. In this paper, only the impact testing is described. The modal testing was completed using the Polytec PSV-500-3D system, including signal generation for the acoustic driver, high speed data acquisition, and initial data post processing. All modal parameters were obtained using Vibrant Technology's ME'scope software (Scotts Valley, CA) [17]. The following acquisition parameters were used for impact testing to acquire the frequency response functions: frequency range 10 - 400 Hz, 3 complex averages per scan location, 6400 frequency lines, impact generated input signal, rectangular window on the output, and a force window on the input. The impact hammer that was used was a PCB (Depew, NY) model 086D80 mini pencil-sized hammer with a vinyl tip. This hammer was selected due to its low mass and good response input in the frequency range of interest. The modal parameter estimation was completed using a single-reference polynomial curve fitting algorithm (AF Poly) developed by Vibrant Technology.

In June of 2014 modal testing was conducted on CMC Mixer 2014 at Air Force Research Laboratory's Structures Facility located at Wright-Patterson AFB, OH. Given the success of the test methodology used in modal testing of CMC Mixer 2013 a similar technique based on excitation of the modes with an impact hammer was used [17]. With the testing schedule allowing additional time to collect data, multiple reference inputs (from 3 impact locations) were used to assist in separating closely-spaced and symmetrical modes. The test-setup for CMC Mixer 2014 was identical to the test-setup for CMC Mixer 2013, with the exception that the 2014 mixer hardware assembly (including the mount plate) was mounted directly to a strong back fixture instead of the slip plate/HTM. The 2014 modal test setup is shown in Figure 12. This setup provided a similar test boundary condition.

The mode shapes, shape frequencies, and percent critical damping were estimated from the frequency response function calculated during both tests. The percent critical damping, in this case, indicates the amount of vibratory energy dissipation per cycle or over time. The lower the damping, the longer it takes to dissipate the vibratory energy. In fatigue applications, modes with lower percent critical damping can be more prone to fatigue failures. Several modes from the analytical analysis results were deemed fatigue critical and were selected to be considered as vibration testing dwell frequencies.

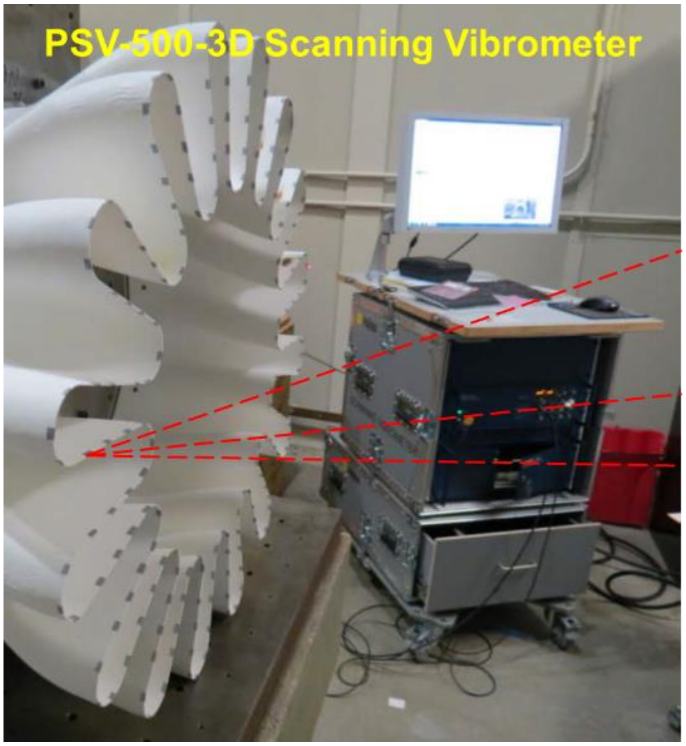


Figure 12: Laser vibrometry was performed on CMC Mixer 2014 while it was attached to the mount plate. A small impact hammer was used to excite the modes

The collected data was processed to produce animated mode shapes, and compared to the FEM mode shape predictions. As an example, a mode shape produced from the experimental data is shown for CMC Mixer 2013 in Figure 13.

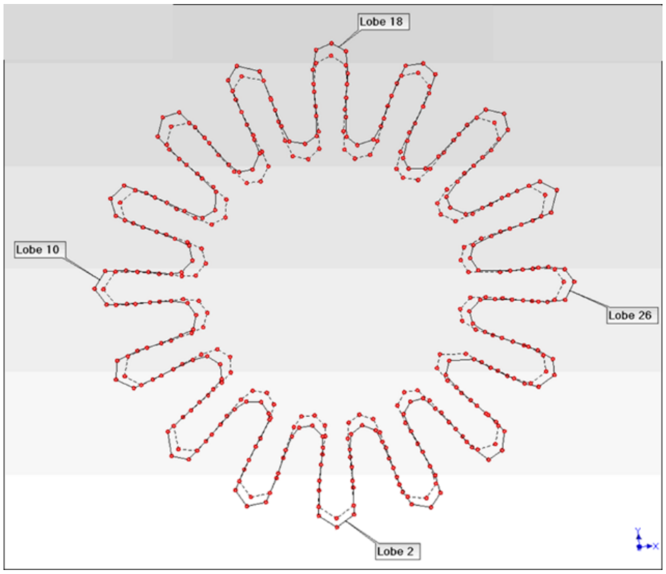


Figure 13: Software-generated animation of mode shape (CMC Mixer 2013) derived from laser vibrometry measurements

Modal Assurance Criteria (MAC) correlation should be completed to ensure the mode shapes compared in the predictions are truly the same shape [18]. The lower frequency modes are fairly easy to match visually but at higher frequencies the complexity of the shapes and the symmetry of the modes require more detailed model validation. Overall, the FEM predictions were accurate for the global mixer modes at low frequencies. The mixer modes which involved lobe bending could generally be matched within a family of modes, but more detailed measurements including the use of more reference inputs would be needed to separate single modes within the family.

2.4.3 Instrumentation of the Mixer and Slip Plate

Control accelerometers were mounted near each of the four corners of the millboard that was bolted beneath the CMC mixer mounting plate (Figure 14). They were oriented in the direction of slip plate translation. The vibration inputs were controlled by the average of the control accelerometer signals. Four response accelerometers were located at two points around the mounting disk. A high temperature single-axis accelerometer (Dytran Instruments, Inc., Chatsworth, CA) was mounted on the mixer mount plate to allow us to obtain readings directly adjacent to the mixer, while a reference triaxial accelerometer was located as shown in Figure 14. The various accelerometers remained in the same location throughout testing.

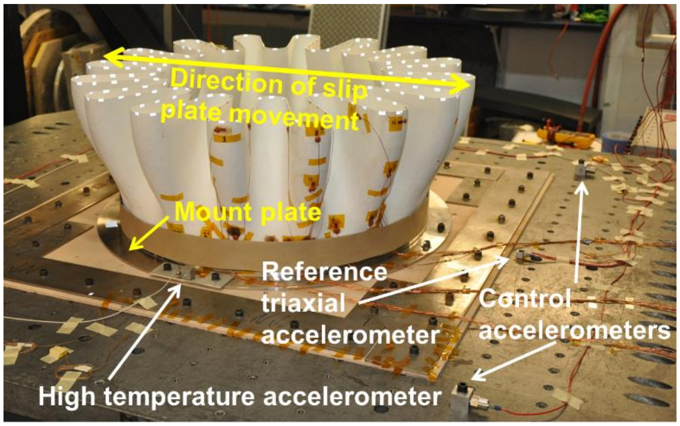


Figure 14. Location of accelerometers on the slip plate

Accelerometers were not attached to the CMC mixers during any of the testing, even though those devices can have a very low mass, because of concerns that the accelerometers/lead wires could possibly influence the results of the vibration testing, especially if they were mounted on “thin-wall” structures such as the lobes. An additional concern about attaching accelerometers to the mixer was that they might cause CMC surface damage to occur during testing or when the accelerometers were removed from the test article.

Linear/uniaxial high temperature, dynamic strain gages (WK-05-125AD-350 fully encapsulated K-alloy gages with high endurance jumper (lead) wires, from Vishay Precision Group – Micro-Measurements, Wendell, NC) were used in this study, based on previous AFRL experience with those gages during testing of CMCs in the 600° (316°C) to 700°F (371°C) range. Note that those testing temperatures exceed the manufacturer's recommended upper use temperature for those strain gages. In 2013 vibration testing, approximately 20 gages were mounted on selected surfaces of the mixer following the natural frequency/mode shape analysis. Bondable printed-circuit terminals were mounted near each strain gage and used as a junction between the main lead wire and the fine jumper wires of the strain gage. A high temperature bonding compound (M-Bond 610 Adhesive from Micro-Measurements) was used to secure the strain gages and the terminal pads to the mixer. The strain gages were applied to several adjacent lobes and the areas beneath the lobes with an apparatus that uses pliable suction cups with built-in heaters/thermocouples to apply the pressure and temperature required to bond the strain gages.

Afterwards, the strain gage's jumper wires and lead wires (that would be connected to signal conditioners) were soldered to the conductive terminal pads. Lead wire cables were secured with both high temperature Kapton tape and Loctite (Henkel Corp., Rocky Hill, CT) 5920 Copper Silicone RTV (room temperature vulcanization) adhesive to minimize movement during testing. Using the capabilities of the GRC SDL and additional signal-conditioning equipment from AFRL, up to 20 strain gages were monitored at a time. In 2013 vibration testing, most of the strain gages performed well at temperatures up to 600°F (316°C), but performance diminished over time during 700°F (371°C) testing. This was possibly due to environmental degradation of the strain gages, but more likely due to "over-temping" the lead-based solder that was used to bond the lead and "jumper" wires. The RTV held up well during the 700°F (371°C) testing.

In testing of CMC Mixer 2014, over 20 high temperature strain gages were mounted within a five lobe region (Lobes 1, 32, 31, 30, and 29) (Figure 15). In comparison to the 2013 instrumentation, greater emphasis was placed on characterizing strain in the areas just beneath the lobes. The strain gages were oriented to collect data in axial, radial, and circumferential directions. Fine multifilar lead wires (#B3301231, MWS Wire Industries (Westlake Village, CA)) were hooked together with the gage jumper wires and those connections were compressed, and then soldered together using Micro-Measurements Silver Solder Paste and a Blazer (Farmingdale, NY) Pencil Torch Model PT-4000. Of the 17 strain gages in use at the start of testing, 12 had failed by the completion of elevated temperature testing, leaving only five functional gages. Some of these strain gages were exposed to temperatures up to approximately 745°F (396°C) due to the aft end of the mixer being hotter than the base. It was clear that testing above 700°F is "pushing the temperature limit" of these gages.

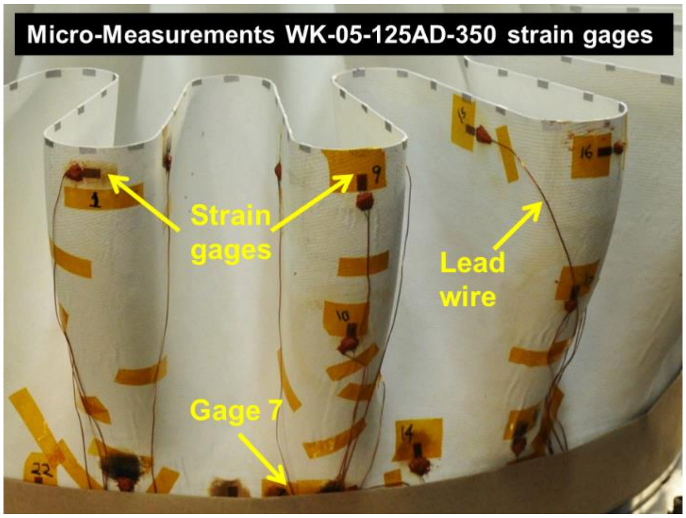


Figure 15. High temperature strain gages mounted on the surface of CMC Mixer 2014

One strain gage (gage #7, see Figure 15) that consistently provided the highest strain reading due to its location did survive the 700°F (371°C) testing. As a means of checking the accuracy of this critical strain gage prior to conducting the final room temperature dwell testing, 11 additional room temperature dynamic strain gages (CEA-03-125UW-350, from Micro-Measurements) were mounted at a symmetrical location on the other side of the mixer and on adjacent lobes. These gages were attached using M-Bond 200 adhesive and standard strain gage mounting procedures. These room temperature strain gages provided very similar readings (in comparison with gage #7 and another surviving high temperature strain gage) during the final room temperature dwell testing, indicating that gage #7 had not only survived the various high temperature tests, but that it was also providing accurate readings.

Overall, evaluating the strain over a range of locations on the surface of the mixer clearly indicated the areas where the loads/strains are highest. The maximum strain gage reading was monitored during dwell tests at a specific frequency in order to maintain a slip plate velocity that provided the desired level of maximum strain within the test article.

Acceleration and strain gage data were acquired on the Vibration Research VR9500 control and data acquisition system. In addition, acceleration, strain, and velocity time history data were acquired simultaneously using the SDL data acquisition system. The SDL data acquisition system was comprised of an HP E8491B VXI front end (HP Mainframe E8403A) with two 16 channel, E1432A input module connected to a Dell desktop computer running NX I-DEAS Test software 6.3.

Other instrumentation included two thin, flexible Type K thermocouples that were run beneath the HTM and the mount plate, and used to monitor the temperature of the slip plate during hot vibration testing, and four similar Type K thermocouples that were bonded to the mixer using Loctite RTV.

2.4.4 Vibration Testing of the Full Scale Mixer

The vibration tests were conducted in the NASA GRC Structural Dynamics Laboratory. Three specific types of vibration testing were used in this study: 1) low level flat random characterization vibration testing [19], 2) high level sinusoidal Inches Per Second (IPS_{rms}) velocity sweep testing (also referred to as sine sweeps or strain survey tests) [20], and 3) dwells at a specific frequency/ amplitude [20]. Each of the 32 lobes (inward and outward pointing) was monitored for possible damage during vibration testing.

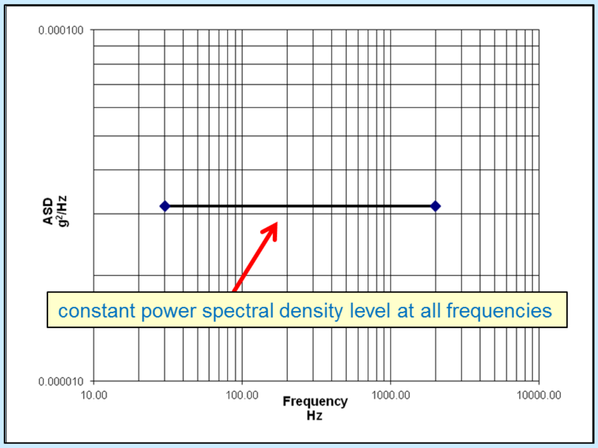
Low Level Flat Random Testing and Strain Survey Testing: Basic Descriptions

Low Level Flat Random Testing:

Low level flat random characterization vibration testing is simultaneous excitation over a band of frequencies (30 - 2000 Hz) at a constant low power spectral density level (0.000032 g^2/Hz) at all frequencies and has a small overall g_{rms} value (0.25 g_{rms}) (Figure 16). It gently exposes the test article to a range of frequencies and excites resonances at a very low level. These excited resonances can be measured before and after higher level vibration testing is performed to see if any structural changes have occurred. This level of excitation is small enough that damage to the mixer is not a concern. In 2013, low level flat random vibration tests were used to characterize natural frequencies of CMC Mixer 2013 from 30 – 350 Hz and allow correlation with ANSYS model predictions. They were also performed before and after IPS velocity sweep testing to determine if any structural changes occurred in the mixer as a result of the testing.

Strain Survey Testing/Sine Sweeps:

High level sinusoidal Inches Per Second (IPS_{rms}) velocity sweep testing is excitation at one frequency at a time with the frequency increasing over time from a starting value to an upper limit (30 - 350 Hz) while the velocity is held at a constant value. While the velocity is held constant over the frequency range being swept, the acceleration is allowed to increase as necessary as the frequency rises to maintain the constant velocity as depicted in Figure 17. As can be seen in the figure, the acceleration levels at the higher frequencies can reach high g levels (2 - 8 g's) that can expose structural and processing-related defects in the test article. IPS velocity sweep tests were used to interrogate the structural integrity of the mixer and to detect processing-related defects.



Frequency, Hz	Test Level
30	0.000032 g^2/Hz
2000	0.000032 g^2/Hz
Test Duration	**Overall Level**
120 seconds	0.25 g_{rms}

Figure 16. Low level flat random vibration characterization testing: simultaneous excitation of resonances at a very low power level over a band of frequencies (30 - 2000 Hz)

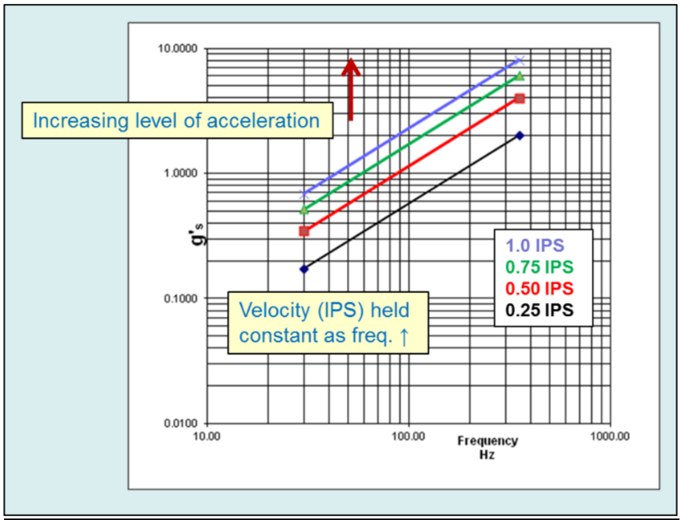


Figure 17: High level sinusoidal Inches Per Second (IPS_{rms}) velocity sweep testing (acceleration levels expressed in g's). Velocity (IPS_{rms}) held constant as frequency increases

Dwell Testing at a Specific Frequency and Maximum Strain:

Vibration dwell tests are performed as fatigue tests that interrogate the structural integrity of the mixer at a specific frequency (mode) with testing performed at a constant velocity. The velocity is selected to produce the desired level of maximum strain (which is selected based on an understanding of the mixer operating conditions and mixer design methodology). The frequency can be adjusted as-needed during the dwell test if there is a mode frequency shift. Most dwell testing was performed at room temperature (RT) because dwell times were limited to about 45 minutes when testing at 700°F (371°C) due to the need to avoid overheating the lubricating oil beneath the slip plate.

CMC Mixer 2014—Room Temperature Exploratory Testing

An initial fixture survey was performed in 2013, but was deemed unnecessary in 2014 since the fixture was unchanged. Exploratory room temperature characterization tests were conducted in three different orientations (Figure 18), for 1) a 0.25 g_{rms} flat random input, 2) a 0.25 IPS_{rms} velocity sweep, and 3) a 0.5 IPS_{rms} velocity sweep. A thorough visual examination of the test article was performed after each exploratory vibration test (9 total), with no significant damage detected.

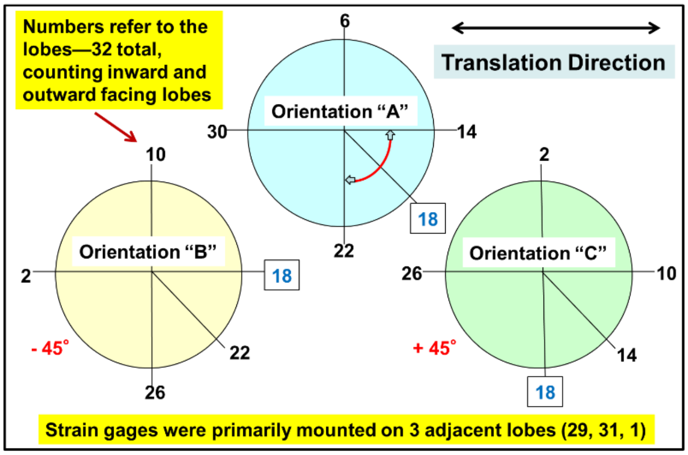


Figure 18: Three orientations of CMC Mixer 2014 that were examined to identify the maximum strain observed. Orientation B was used for the remaining testing

This testing was performed because the majority of the strain gages were mounted on 3 mixer lobes (approximately one quadrant). Rotation of the mixer allowed more thorough investigation of the strains produced during vibration testing. Major modes between 30 - 350 Hz were identified and the strain levels of 17 strain gages were monitored to detect the maximum strain produced during the exploratory testing. The data was collected and processed by the SDL Vibration Research (VR) control and data acquisition system. After determining which orientation created the largest strain (as measured by the strain gages), testing continued with the test article re-oriented in the "- 45º position" (Orientation B, with Lobes 2 and 18 oriented in the slip plate translation direction). At this point, only 13 strain gages were functioning. The reason the other strain gages stopped providing data was undetermined. Some very small flakes of matrix material were observed on the mount plate or outside the mixer following these tests. The flakes might have come from areas that had been repaired with additional matrix material added to them during the processing of the mixer.

CMC Mixer 2014—Room Temperature Dwell Testing

The first 1,000,000 cycle constant velocity dwell at the 2nd natural frequency and a specified microstrain limit was conducted before any high level 1.0 IPS_{rms} sine sweep testing or elevated temperature tests. Based on previous experience, the team had concerns about losing more strain gages during 700°F (371°C) testing, and the potential impact of 1.0 IPS_{rms} velocity sweep testing on the mixer was unknown. The dwell test was interrupted twice prior to completion, and inspections were performed. The highest strain was occurring at gage #7 throughout this testing. The torque of the attachment ring bolts (both those attaching the mixer to the attachment ring, and those holding the ring to the mount plate) was checked. It appeared that slight loosening of some of the locknuts had occurred, or perhaps the bolts had "settled" during testing.

Furnace for Elevated Temperature Vibration Testing

A number of approaches for heating the mixer during a vibration test were considered. The main requirements were that the furnace could not contact the slip plate or the component during testing, and it needed to be able to heat the mixer to 700°F (371°C) and maintain that temperature while sine sweeps or dwell tests were performed. Other concerns included wanting the component's inner surface to have a higher temperature than its outer surface (thus, the heating system should be placed within the mixer), wanting to minimize the thermal gradient in the axial direction of the mixer, needing to be able to achieve and maintain the desired 700°F (371°C) maximum temperature, and having the ability to monitor the temperature of the large, complex-shaped mixer and control the temperature throughout the component.

After considering various approaches, a suspended "box furnace" that essentially enclosed the mixer, but did not touch the test article or slip plate, was selected as the best approach based on a number of factors including cost, safety, ability to control the temperature of the component, ability to measure component deformation during hot vibration testing, etc. The furnace was designed and constructed at NASA GRC, building on GRC's previous experience in developing custom furnaces for unique elevated temperature mechanical property testing. It was lowered over the article and then suspended slightly above the slip plate using a 5 ton capacity crane (Figure 19). The furnace was secured by tie lines during testing, to prevent any movement of the furnace. It rested on wood blocks during component inspections and during breaks in the testing, as a safety precaution. The furnace was grounded to prevent electrical shock, and other potential safety issues were addressed.

The walls of the furnace were made of high temperature millboard (HTM). The inner and outer wall surfaces were covered with steel mesh, to hold the millboard in place within the steel frame of the furnace. There were two removable doors/covers on the top of the furnace (also made of HTM, with steel mesh on the top surface). Each cover had 2 fused quartz windows that were installed to allow use of laser vibrometry during testing. They also allowed us to see into the furnace during hot vibration testing. The front of the furnace had a large fused quartz window (Figure 19), for allowing use of laser vibrometry to monitor component deformation. To minimize heat loss around the base of the mixer, the furnace had 2 "sliding bottom panels" made of HTM with semi–circle cut-outs that were slid into place at the bottom of the box furnace, leaving a small open gap in the furnace around the base of the mixer, to prevent the furnace from touching the mixer (Figure 20). The top surfaces of those panels were covered/insulated with 0.090" (2.3 mm) thick silica fabric.

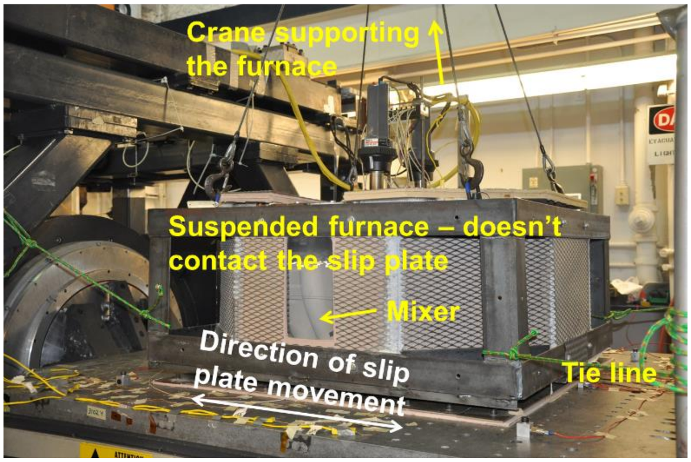


Figure 19. Furnace suspended above the slip plate

The inner surface of the mixer was heated with a combination of radiative heating (via six 15" (38.1 cm) 2400W Watlow (St. Louis, MO) Firerod Cartridge Heaters) and convective heating (via two in-line, heavy-duty 1750W STEINEL (Bloomington, MN) HG4000 E heat guns that provided flowing air at temperatures up to 1100°F (593°C)). As shown in Figure 21, the cartridge heaters were located within a cylindrical septum (which was made of stainless steel, and painted black), and the hot air from the heat guns also flowed into the septum. The septum helped provide a uniform distribution of radiative heat to the component, and the hot flowing air from the heat guns provided heat to the inner base of the mixer and helped circulate heat within both the mixer and the furnace. This appeared to compensate for heat losses through the gap at the bottom of the furnace.

The temperature of the furnace was measured with one 12" OMEGA Engineering (Stamford, CT) Type K thermocouple that was positioned within the septum. The thermocouple was connected to a programmable controller, which controlled the current provided to the heater cartridges and allowed us to heat at specific rates. The heat guns were manually adjusted/ controlled, periodically increasing the temperature of the hot air they produced as the furnace temperature increased. A similar methodology for heating the furnace was used in each of the hot vibration test runs. The furnace was typically heated to a series of set points at a constant heating rate of 17°F (9.4ºC)/minute. Note that a 700°F (371°C) test means that the mixer had achieved that temperature on its outer surface (minimum). Three or four small, flexible Type K thermocouples (TC) were attached to the mixer to monitor the temperature as follows: Mixer outer surface—one TC mounted on the base of the mixer, one mounted near the tip of an outward pointing lobe, and one mounted near the tip of an inward pointing lobe; Mixer inner surface—one TC mounted near the tip of the same inward pointing lobe. These were attached with Loctite 5920 Copper Silicone RTV adhesive, with the intent of keeping the TC bead in contact with the CMC surface. The axial thermal gradient was approximately 48°F (27°C) on average (based on an average of surface temperatures at the aft end of the mixer). Temperature data for the TCs on the opposite sides of an inward pointing lobe indicated that the thermal gradient across the part at that location was approximately 60°F (33°C). The gradient through the lobes of a mixer under actual operating conditions will be greater.

Four layers of 0.09" thick silica fabric (insulation cut into circular pieces) were bonded with Loctite 5920 RTV to the top surface of the mount plate to help prevent heat transfer into the slip plate. Given the presence of the HTM beneath the mount plate, it was assumed that the gradual increase in the slip plate temperature primarily resulted from heat conducted into the slip plate through the bolts that held the mount plate in place.

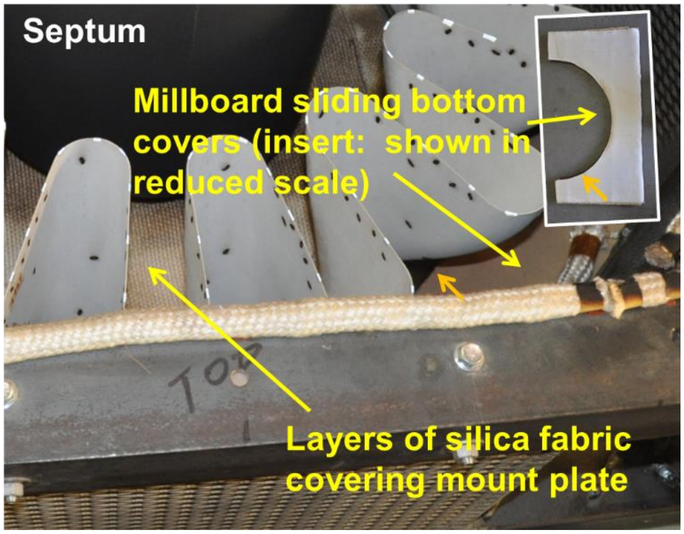


Figure 20. Minimization of heat loss via millboard sliding bottom covers and insulating fabric bonded to the mount plate

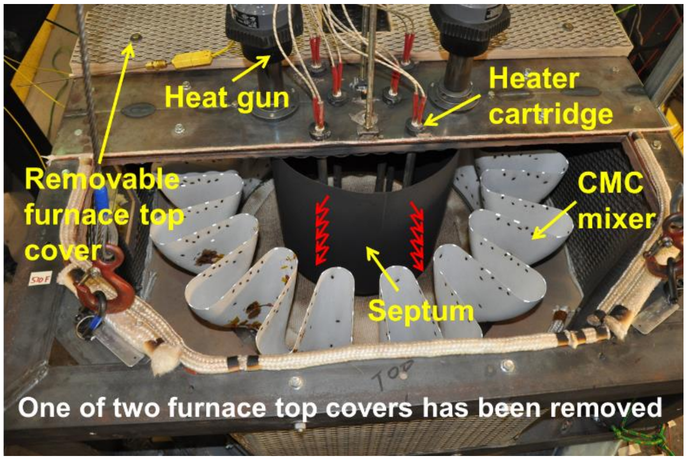


Figure 21. Interior of the furnace and CMC Mixer 2013

CMC Mixer 2014—Elevated Temperature Vibration Testing

Elevated temperature 0.5 IPS$_{\text{rms}}$ velocity sweep testing was performed at 600ºF (316°C) and 700°F (371°C) with no cool down for inspection between tests, to determine the effect temperature had on the mixer modes and strain levels. This was followed by an inspection of the article and a RT 0.5 IPS$_{\text{rms}}$ velocity sweep. The maximum strain (gage #7) observed at 700ºF was about 10% higher than that observed at 600ºF or RT, and the first several natural frequencies were fairly similar (at elevated temperature, those modes occurred within 1 Hz of the frequency where modes were observed at RT). We did not perform duplicate tests under those conditions, due to concern about the strain gage durability. Next, a 700ºF 100,000 cycle constant velocity dwell at the 2nd natural frequency and a specified microstrain was performed to check the CMC mixer durability at elevated temperature. The mixer showed no significant visible signs of degradation following the dwell. A final 700ºF high level 1.0 IPS$_{\text{rms}}$ velocity sweep was run. The maximum strain observed was within an acceptable limit. Following this test, a minor defect associated with the edge of a ply was observed.

CMC Mixer 2014—Room Temp. Vibration Testing

After the high temperature testing was complete, the torque of the attachment bolts was checked to verify that the locknuts were tight. Then, a 1.0 IPS$_{\text{rms}}$ velocity sweep was performed. Another minor defect associated with the edge of a ply was observed following the test. Next, as described in the Instrumentation section of this paper, 11 new RT strain gages were attached to the CMC mixer, as only five of the original high temperature strain gages were still functioning. It was important to try to confirm that gage #7 was providing accurate readings. Seven of these new gages as well as the five functioning original gages were used during the final 1,000,000 cycle constant velocity dwell. Testing was conducted at the 2nd natural frequency and a specified maximum strain level. The dwell test was interrupted twice prior to completion, and inspections were performed at each break. This was followed by a final 0.5 IPS$_{\text{rms}}$ velocity sweep, which indicated a maximum strain consistent with those observed in earlier similar tests. Additional inspection after the mixer had been removed from the mount plate revealed one other minor defect that was associated with the edges of a ply.

2014 Vibration Testing Results--Conclusion

CMC Mixer 2014 was successfully vibration tested, exhibiting good durability during dwell testing, and yielding a significant amount of data from the RT and elevated temperature strain surveys (sine sweeps). That data allowed us to map out the strains/stresses in Lobes 1, 31, and 29 during testing, and it was compared with previous modeling/analysis results. In contrast to the testing of CMC Mixer 2013, a through-thickness crack did not form in CMC Mixer 2014. Only three minor defects were observed that appear to have been caused by the testing. They were associated with the edges of plies, and possible loss of matrix material in those areas. As experienced in previous elevated temperature testing, some (seven) of the high temperature strain gages failed. However, these gages had been used above the recommended "use temperature", and some had been exposed to temperatures above 700°F due to the thermal gradient along the axial direction of the mixer. While the testing that was performed allowed the team to examine the durability of the full scale CMC mixer, one limitation of vibration testing the mixers is that it doesn't provide the pressure effect and significant through-thickness thermal gradient created by the flowing hot exhaust gases and cold air in the actual mixer operating environment.

3. SUMMARY

NASA GRC teamed with Rolls-Royce LibertyWorks®, COI Ceramics, Inc., and Support Services, LLC, in the Environmentally Responsible Aviation (ERA) Project to achieve TRL 4 through the design, fabrication, and testing (validation of the aerodynamic and acoustic performance) of a subscale Ox/Ox exhaust mixer that was designed for true flight environment. Next, AFRL WPAFB joined the team to support the design, fabrication, and successful vibration testing of a full scale Ox/Ox CMC mixer that was sized for a RR AE3007 engine. NASA and RR developed this technology together under a Non-reimbursable SAA to increase TRL from 3 to ≈5. The vibration test matrix, which was designed to clear the component for TRL 6 ground-based AE3007 engine testing, was completed in the GRC Structural Dynamics Lab in July, 2014. That testing included sine sweeps (performed from 30 - 350 Hz at RT, 600°F (316°C), and 700ºF (371°C), at velocities ranging from 0.25 to 1.0 Inches Per Second (IPS$_{\text{rms}}$)) and dwells (performed at RT and 700ºF, at the 2nd natural frequency, and specified maximum microstrain levels). That frequency was selected because it is where the team observed the highest strains during exploratory sine sweeps. Two 1 million cycle dwells were performed at RT and one 100,000 cycle dwell was performed at 700ºF. While deformation of the lobes was easily observed during the dwell tests, the flexibility of the CMC component kept it from experiencing significant damage. Only 3 minor defects were observed following testing of the full scale component. The next step will be ground-based engine testing of "CMC Mixer 2014" at Rolls-Royce in Indianapolis, IN.

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