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CERAMIC COMPOSITE ATTACHMENTS FOR TRANSMISSION OF HIGH TORQUE LOADS

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ABSTRACT

The use of fiber-reinforced ceramic matrix composites (FRCMC) for advanced turbopump (T/P) hot-section components offers a number of potential advantages relative to the use of 'conventional' materials. Among these advantages are reduced weight, enhanced life with reduced maintenance and improved performance achievable by increasing the turbine inlet temperature. FRCMC are, however, emerging materials, and their design and analysis present unique challenges. These composites have relatively low thermal expansion coefficients and low strain-to-failure characteristics, and they have nonlinear, anisotropic properties. These characteristics particularly complicate the design of attachments to mating metallic components within a T/P.

In an ongoing program*, an FRCMC stator and rotor for a rocket engine T/P are being developed for eventual ground test demonstration. The rotor attachment is designed to transmit high torque loads and provides an example of a design methodology which is compatible with current analytical capabilities. The approach used and described herein applies an empirically derived materials properties data base in combination with macromechanical analysis to reach a solution to this design challenge. This example demonstrates both the capabilities and the limitations of current design and analysis practices and provides direction for future development. A curvic coupling was chosen to meet the specific design goals and will be fabricated and tested to verify the design.

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NOMENCLATURE

T/P	turbopump
FRCMC	fiber-reinforced ceramic matrix composites
T/M	turbomachinery
Mk44F	Mark 44 fuel (hydrogen) turbopump
LOx/LH_2	liquid oxygen/liquid hydrogen
C/SiC	carbon fiber-reinforced silicon carbide
CVI	chemical vapor infiltration
2D	2-dimensional
OD	outer diameter
ID	inner diameter
WI	Williams International

INTRODUCTION

Application of FRCMC to rocket engine turbomachinery (T/M) has the potential to: reduce component weights, improve life and decrease maintenance of components subject to high thermal stresses and/or to erosive and corrosive rocket engine environments, and improve performance or efficiency (principally by increasing the turbine inlet temperature) (Brockmeyer and Schnittgrund, 1990). FRCMC are, however, emerging materials, and their ability to withstand the extreme conditions imposed by rocket engine use has not been validated. Of particular concern is the relative lack of anchored, design and analysis methods for these complex (nonlinear, anisotropic) materials which results in the need for substantial levels of empirical verification of analysis predictions. Gaining confidence and eventual acceptance of these materials, then, requires design and analysis of representative components followed by validation through fabrication and testing.

Methods for FRCMC design and analysis continue to be developed and improved. Laminate level analytical methods (Duffy et al., 1993; Thomas and Wetherhold, 1993) for in-plane reliability based on statistical, fast fracture predictions

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are undergoing rapid development. These analyses are valid for composites composed of unidirectional lamina but are not yet developed and validated for woven laminate structures. Micromechanical analysis methods (Rubinstein, 1993) also have potential to support future designs but are not currently suited to analysis of complex components.

In a NASA Lewis funded program, an FRCMC stator and rotor are being designed and analyzed and, ultimately, will be fabricated for test within a rocket engine T/P. The baseline turbopump selected for this effort is the Mk44F** turbopump (Fig. 1) which is a gas generator cycle, liquid oxygen/liquid hydrogen (LOx/LH_2) combustion product propelled T/P. The Mk44F is suitable for demonstrating a number of key characteristics of the FRCMC components on a relatively small, economical scale. To demonstrate the effects of increased turbine inlet temperature, the baseline Mk44F T/P will be modified to increase the inlet temperature from 870°C (1600°F) typically used for conventional stator and rotor materials (e.g., superalloys) to 1200°C (2200°F) which is compatible with currently available and previously identified FRCMC materials. To achieve the increased inlet temperature, current plans call for the use of a water-cooled turbine inlet manifold fabricated from conventional materials for ground tests. In the future, high temperature capability manifold materials will be used for a flightweight T/P. Also, to simplify and reduce cost of the ground test demonstration, the baseline 2-stage turbine will be modified to a single-stage FRCMC turbine.

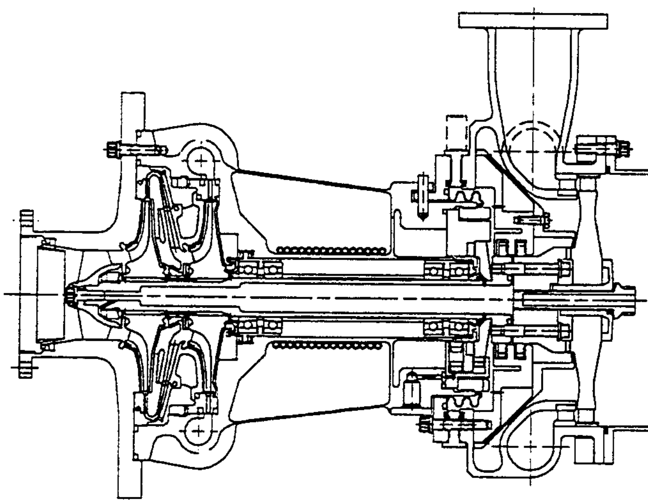

Fig. 1
Modified Mk44F T/P with water-cooled manifold for ground test demonstration of FRCMC stator and rotor

In previous studies, the preferred material for near-term demonstration of FRCMC materials capabilities was identified to be polar woven, carbon fiber-reinforced silicon carbide (C/SiC) fabricated by chemical vapor infiltration (CVI)(Brockmeyer and Schnittgrund, 1990). Use of polar weaving tailors the in-plane load-bearing capability of the FRCMC to the high in-plane loads encountered in the rotor. C/SiC has been shown to meet the thermal (Eckel and Herbell, 1990) and environmental (Misra, 1990; Herbell et al., 1991) demands imposed by the hydrogen-rich steam combustion environment of the T/P hot section. CVI processing meets near-term, component fabrication requirements.

** The MK44F is a fuel (hydrogen) turbopump originally designed as an auxiliary power unit under Air Force Contract.

DESIGN AND ANALYSIS PROCEDURES

A structurally acceptable profile for the rotor had previously been designed and analyzed, using an analogous approach to that described for the attachments. Initial concern in profile design focused on the high in-plane mechanical stresses generated during rotor operation, including both bore burst stresses and flow pressure bending stresses expected at the blade tips. However, as the design progressed, out-of-plane stresses (e.g., interlaminar shear and through-thickness tension) were found to have a major influence on the profile design due to the low values of these properties for 2D C/SiC. Throughout the design process, fabrication constraints were also considered. This was accomplished through a concurrent engineering approach with the materials fabricator. For initial analyses, the vendor's (DuPont Advanced Composites, Wilmington, DE) materials properties data base (Tbl. 1) was used, although this data base has been expanded and refined for subsequent analyses.

Tbl. 1
C/SiC materials properties summary
(for 0°/90°, balanced lay up)

PHYSICAL PROPERTIES			
PROPERTY	UNITS	NOMINAL VALUE	
Fiber Content	Vol. %	45	
Density	Gm/cm³	2.1	
Porosity	Vol. %	10	
MECHANICAL PROPERTIES			
PROPERTY	UNITS	TEMPERATURE	
		23°C	1200°C
Tensile Strength	MPa	425	530
Elongation (Tensile)	%	0.93	1.0
Initial Young's Modulus (Tensile)	GPa	76	120
Compressive Strength (In-Plane)	MPa	520	
Flexural Strength	MPa	454	
Flexural Elongation	%	0.72	
Flexural Modulus	GPa	68.3	
Cross-Ply Tensile Strength	MPa	11.9	
Shear Strength (Interlaminar)	MPa	26	
Fracture Toughness	MPa•m$^{1/2}$	40	
THERMAL PROPERTIES			
PROPERTY	UNITS	TEMPERATURE	
		23°C	1000°C
In-Plane CTE*	10^{-6}/°C	3	3
Thru-Thickness CTE	10^{-6}/°C	5	5
In-Plane Diffusivity	10^{-6}m²/S	11	7
Thru-Thickness Diff.	10^{-6}m²/S	5	2
Specific Heat	J/kg°C	620	1400
Total Emissivity	---	0.8	0.8
In-Plane Conductivity	Wm^{-1}•°C^{-1}	14.3	20.6
Thru-Thickness Cond.	Wm^{-1}•°C^{-1}	6.5	5.9

* - Coefficient of Thermal Expansion

The properties data shown are for a 50:50 (balanced), orthogonal, plain woven, fiber architecture. For the initial turbine disk analyses a balanced, 50:50 polar woven fiber architecture was assumed which is analogous to the balanced orthogonal architecture. That is, the hoop (or circumferential) fibers of the polar weave correspond to the 0° orthogonal fibers, and the radial fibers correspond to the 90° orthogonal orientation. Future evolutions of the polar layup will further tailor the structure and may employ imbalanced fiber architectures.

Using the torque loads anticipated for the modified Mk44F T/P design, a series of possible attachments were then evaluated. The objectives were to maintain acceptable loads within the rotor profile while simultaneously achieving acceptable loads within the attachments or couplings. In addition to torque transmission, the attachment must maintain rotor centering to the shaft during the severe transient and mainstage operation. Analyses were based on fast fracture criteria. Statistically derived design allowables were used when sufficient data were available, or factors of safety were applied where data were inadequate for statistical analysis. Coupon tests were run which verified durability of C/SiC under the proposed operating conditions and which support use of fast fracture properties. Coupon tests showed that only extreme conditions of thermal shock combined with environmental exposure resulted in degradation of properties.

Analyses were macromechanical and used 2-dimensional (2D), ANSYS finite element models. Orthotropic materials properties were input to determine principal in-plane and out-of-plane stresses. Initial cases considered mechanically induced loads and used as-received, room temperature materials properties. Refined analyses of the preferred attachments additionally considered effects of mechanical cycling and thermal loading effects. The design of the couplings followed an evolutionary approach, drawing upon lessons learned in previous cases until an acceptable, conceptual design was developed.

RESULTS AND DISCUSSION

Conventional coupling methods used with metallic rotors were modified for use with the FRCMC rotor profile. Loads were analyzed for representative operating conditions as described below.

Stud Drive

The possibility of using studs to carry the torque loads was evaluated (Figs. 2-3). The model included 4 @ 0.64 cm (1/4") diameter through-holes located at a radius of 3.56 cm (1.4") on the 16 cm (6.3") outer diameter (OD) disk. Qualitative consideration was given to other hole diameters. Results were unacceptable primarily due to the high hoop stresses (366 MPa [53.1 ksi]) within the holes. Consequently, the holes were moved outward to avoid the high inertial hoop and radial loads encountered at the 3.56 cm (1.4") radius. Very high Hertzian contact loads (approximately 331 MPa [48 ksi]) for a typical bolt at this location combined with the inertial loading (262 MPa [38 ksi]) also were considered unacceptable.

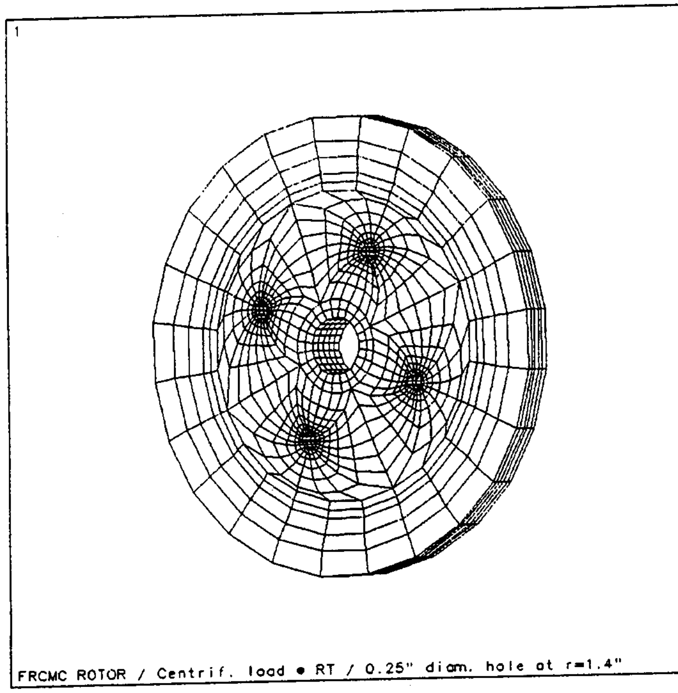

Fig. 2
Stud drive (overview)

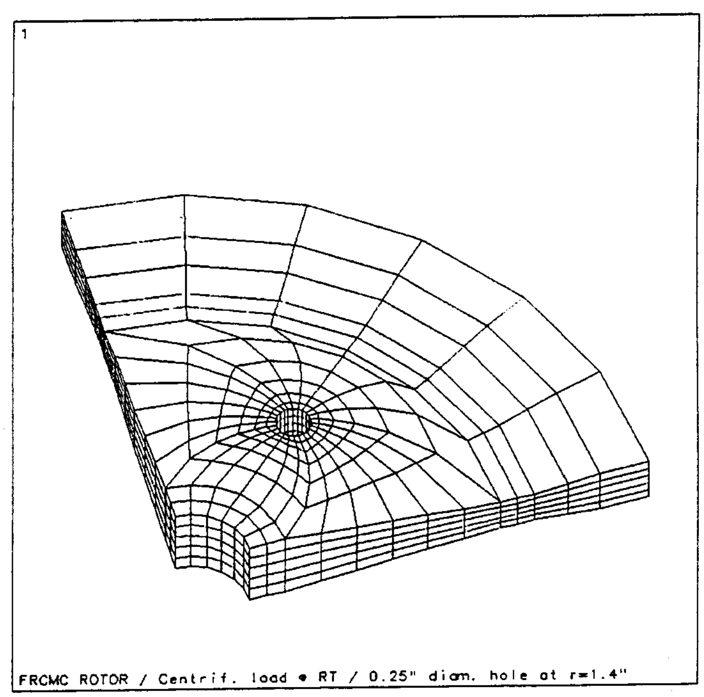

Fig. 3
Stud drive (detail)

Polygonal Shaft

Use of a 3-lobed polygonal shaft with a nominal 2 cm (0.8") minimum bore (compatible with fabrication constraints) (Figs. 4-5) resulted in unacceptable (384 MPa [55.7 ksi]) hoop loads from centrifugal loading only. Consideration of a reduced bore diameter resulted in unacceptable hoop inertial stresses due to the concentration of loads in the reduced radius of the lobes. Torque loading resulted in an additional 69 MPa (10 ksi) hoop stress.

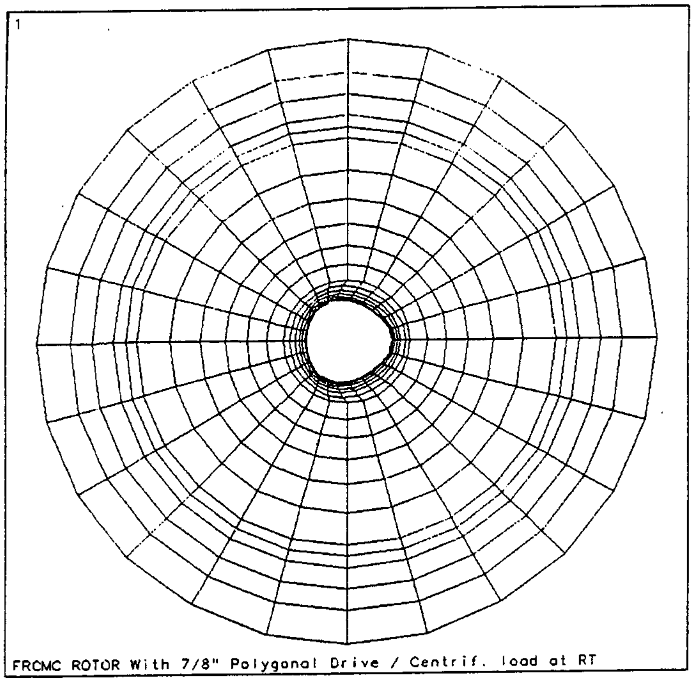

Fig. 4
Polygonal shaft drive (overview)

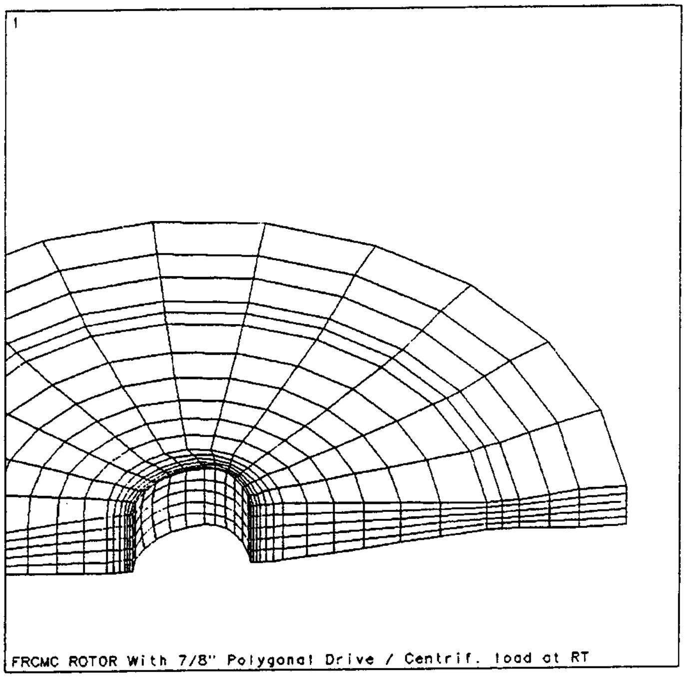

Fig. 5
Polygonal shaft drive (detail)

Extruded, Splined Hub

An extruded, splined flange with a 0.8 cm (0.3") fillet was considered (Fig. 6). In addition to centrifugal loading, various hub face pre-loads were added to reduce through-thickness tension and interlaminar shear loads. The preferred pre-load was estimated to be 14 MPa (2 ksi). Even with this pre-load, interlaminar shear and through-thickness tensile loads were unacceptable (40 MPa [5.8 ksi] and 27 MPa [3.9 ksi], respectively) due to the steep taper angles in the vicinity of the flange.

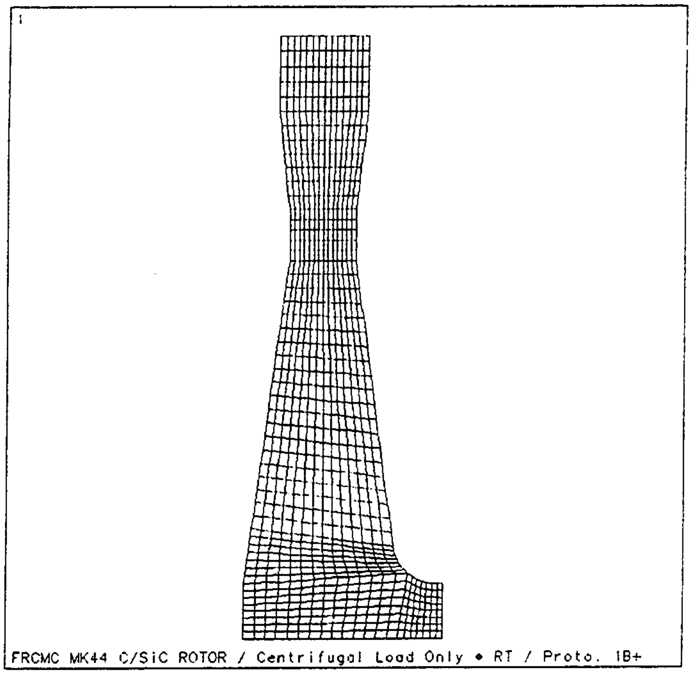

Fig. 6
Extruded, splined hub

Inner Diameter (ID) Radial 'Gear'

Use of an ID (hub) spur gear type arrangement (Fig. 7) was also found unacceptable. The stress concentration in the vicinity of the gear teeth resulted in excessive (525 MPa [76.1 ksi]) hoop stresses.

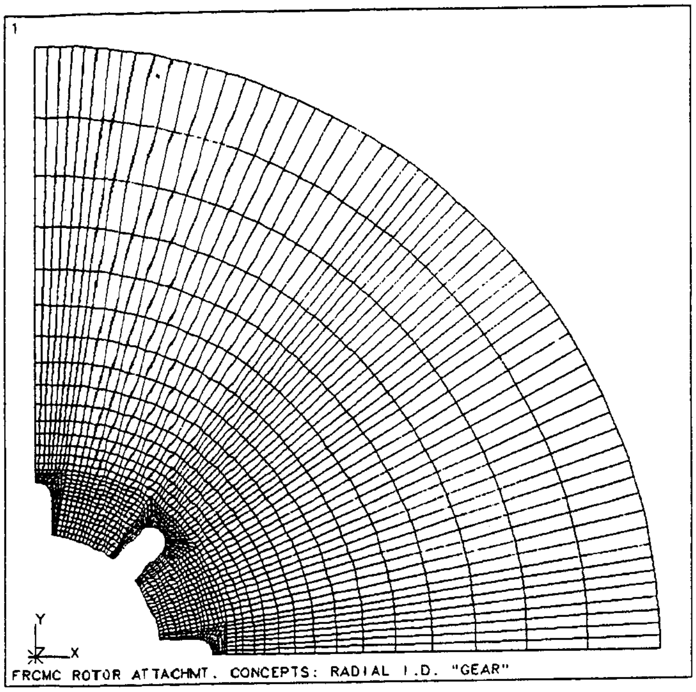

Fig. 7
ID radial 'gear'

Hub Internal Face Spline

The possibility of using a hub internal spline (Figs. 8-9) was evaluated with the previously developed rotor profile. No significant changes were observed in hoop and radial loads vs. the profile without couplings, but interlaminar shear (35.2 MPa [5.1 ksi]) and through-thickness tension (39.2 MPa [5.7 ksi]) loads were unacceptable due to the sharp taper in the extruded section of the hub where the splines were located. An alternative was evaluated (Fig. 8) without extrusion of the hub section. Hoop loading was slightly reduced to 277 MPa [40.2 ksi], but isolated areas of unacceptable interlaminar shear and through-thickness tension loading were observed.

Curvic Coupling

A standard curvic coupling, precision face spline with 20 teeth (Fig. 10) was analyzed using the rotor profile. The teeth were located at a 5.3 cm (2.1") ID based on initial T/P conceptual design requirements. Inertial loads (60,000 rpm at room temperature) were analyzed first. Based on inertial loading only, this was determined to be the preferred coupling concept. Hoop loads (325 MPa [47.1 ksi]) were nominally acceptable. Peak radial stress was 163 MPa (23.7 ksi). A peak interlaminar shear load of 32.4 MPa (4.7 ksi) was found in an isolated volume near the curvic fillet. This stress was greater than allowable, but compressive loading

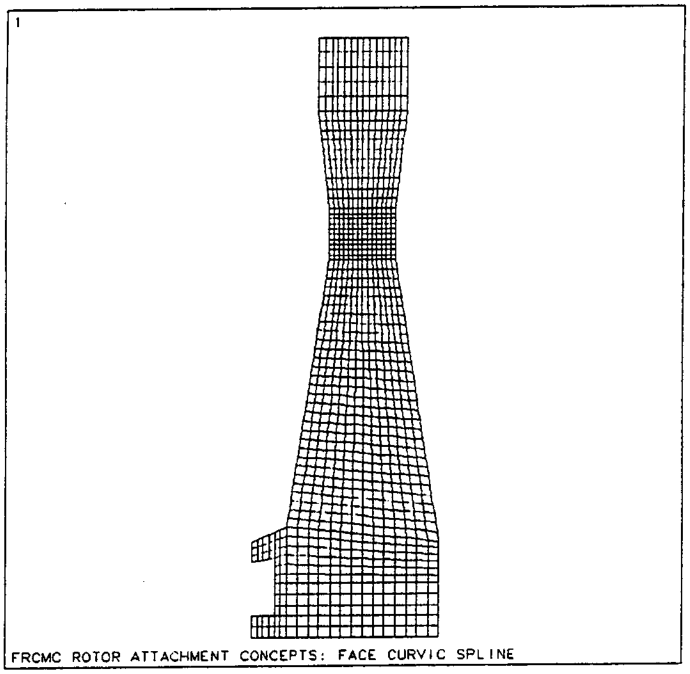

Fig. 8
Hub internal face spline concept no. 1

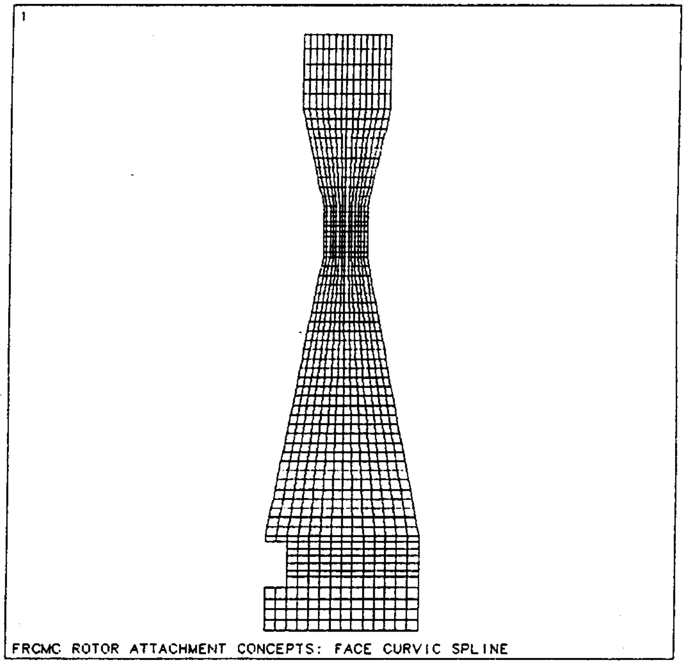

Fig. 9
Hub internal spline concept no. 2

from the metallic, mating component had not been factored into the analysis. Also, previous studies had indicated that ability to survive high, calculated interlaminar shear loads in isolated regions may be greater than anticipated and requires experimental verification. Based on the above considerations, this curvic design was tentatively considered acceptable, and more extensive analyses were performed.

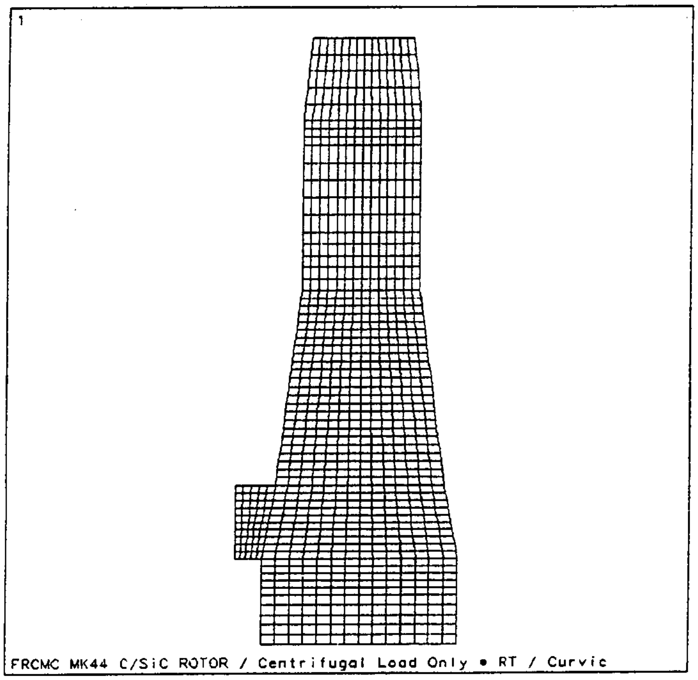

Fig. 10
Curvic coupling

Additional stresses could be expected to be generated as a result of thermal expansion mismatch between the FRCMC disk and the mating metallic component. 2D thermal analyses were run of the disk in the vicinity of the curvic. Results of this modeling are being input to a more detailed structural model which considers the impact of the thermal expansion mismatch. Initial results indicate that the difference in radial growth between the metallic and FRCMC components is acceptable. Further analysis of this concept is in progress. An allowance for limited relative growth can be accommodated within the tooth geometry.

SUMMARY AND CONCLUSIONS

Use of FRCMC components in advanced T/M requires the development of attachment and coupling concepts that are compatible with the nonlinear and anisotropic properties of these materials and that account for the relatively low thermal expansion and strain-to-failure characteristics of the material. The low interlaminar shear and through-thickness tension strengths of these materials require more detailed analysis than that for conventional, isotropic materials. Current analytical tools are limited to macromechanical analysis and, in practice, an empirical, evolutionary design approach proves to allow for effective utilization of the available tools.

For the example discussed, a curvic coupling provides an apparently effective solution to the challenge of transmitting the high torque loads generated by a rocket engine turbopump. Work is continuing to further analyze the thermal expansion mismatch effects, and preliminary results are promising. Ultimately, experimental validation of these concepts is needed. As a first step in this direction, machining studies are planned to validate capabilities of fabricating curvic couplings as part of an FRCMC component. Following these machining studies, an FRCMC curvic coupling will be fabricated and tested to verify its torque handling capabilities.

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