10. Appendices

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Appendix A — FE Mesh & Model Details

A.1 Overview

This appendix records the finite element (FE) model basis for the HP Compressor Casing (HPCC) used in §4–§6, including mesh statistics, element formulations, contact definitions, coordinate frames, and boundary conditions. The model is configuration-controlled per Table 2-1 and §2.1.

A.2 FE Model Identification

Model Name: [HPCC\_FE\_MODEL\_NAME]

Model Version / Rev: [FE\_MODEL\_REV]

Pre/Postprocessor: [PREPOST\_TOOL / VERSION]

Solver: [ANSYS Mechanical APDL / Workbench — VERSION]

Units: [UNIT\_SYSTEM — e.g., N, mm, s, °C]

Global Coordinate System (GCS): [GCS\_NAME]

A.3 Mesh Statistics & Quality

Table A-1 FE Mesh Statistics & Quality Metrics

Item Value Notes

Element Types [SOLID186/187/…], [SHELL181], [BEAM188], [MASS21] Use of [CONTACT174/TARGE170] for nonlinear contact

Total Elements [#] Post-suppression / analysis-ready

Total Nodes [#]

Avg. Element Size (bulk) [Δ] [units] Targeted to capture [HPCC\_#1 MODE BAND]

Min / Max Jacobian [min]/[max] ≥ [QUALITY\_LIMIT]

Skew / Warpage (95th %) [#/range] Within [PROGRAM\_LIMITS]

Aspect Ratio (95th %) [#/range]

Contact Pairs [#] See A.5

Rigid/Remote Elements [#] See A.6

DOF Count (active) [#]

Lumped Mass (added) [value] [Purpose, e.g., fixtures]

Figure A-1 FE Mesh Density & Hot-Spot Regions — [FIG\_A1\_ID] (Reserved; to be inserted)

A.4 Material Assignment

Materials per Appendix B (Table B-1).

Element set → material map:

[SET\_A] → [ALLOY/SPEC/HT]

[SET\_B] → [ALLOY/SPEC/HT]

Coatings/liners modeled as [SHELL/THIN SOLID/ORTHO-ISO] with thickness [t] per [DRW\_NO]/[REV].

A.5 Contacts

Contact Types: [Bonded / Frictional μ=[…] / Rough]

Normal Stiffness: [PROGRAM\_DEFAULT or VALUE]

Tangential Behavior: [Penalty / μ] = [VALUE]

Contact Table:

[CONTACT\_PAIR\_ID]: [MASTER\_SET] ↔ [SLAVE\_SET], Type [TYPE], Status [TIED/ACTIVE], Rationale [RATIONALE].

A.6 Interfaces & Load Application

Interfaces (Remote Point — Distributed mapping unless rigid):

[IFACE\_A] (Frame [FRAME\_A]) — Type [RBE3-like], DOFs [UX UY UZ RX RY RZ].

[IFACE\_B] (Frame [FRAME\_B]) — Type [RBE3-like], DOFs [UX UY UZ RX RY RZ].

Interface node/element groups are listed in Table 5-7.

A.7 Boundary Conditions

Kinematic constraints per §5:

[IFACE\_A] — [Constraint definition]

[IFACE\_B] — [Constraint definition]

Symmetry/periodicity: [IF\_USED] [DETAILS/ANGLE].

Gravity: [ON/OFF] at [g] in [axis] (for pre-stress if required).

A.8 Mass Properties (Validation Snapshot)

Property Model Target (CAD/[WEIGHT\_REPORT\_ID]) Δ

Mass [kg] [VAL] [VAL] [Δ%]

CG (x,y,z) [mm] [VAL,VAL,VAL] [VAL,VAL,VAL] [Δ]

Ixx/Iyy/Izz [kg·mm²] [VAL/VAL/VAL] [VAL/VAL/VAL] [Δ%]

A.9 Mesh Convergence (Hot Spots)

Locations evaluated: [LOC-1], [LOC-2], [LOC-3].

Metric: peak σ\_vm(t) in §6.1 and σ\_a in §6.4.

Result: refinement from [h]→[h/1.5] changed peaks by [Δ%], within [≤ X%] target. Mesh locked at [ELEMENT\_SIZE\_SETTING].

A.10 Model Files (See Appendix G)

Geometry: [PATH]/[MODEL].agdb

Mesh: [PATH]/[MODEL].cdb

APDL/WB project: [PATH]/[PROJECT].wbpj

Hashes and owners in Table G-1.

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Appendix B — Materials, Temperature-Dependent Properties & Allowables

B.1 Scope

This appendix lists temperature-dependent properties, local allowables, and fatigue data used for §5–§7.

B.2 Material Identification

Table B-1 Temperature-Dependent Material Properties (E, σ\_y, σ\_u, α, ν)

Material Spec/Heat Treat T [°C] E [GPa] σ\_y [MPa] σ\_u [MPa] α [µε/°C] ν Source

[ALLOY/SPEC/HT] [SPEC] [T\_i] [E\_i] [σy\_i] [σu\_i] [α\_i] [ν\_i] [MAT\_DB\_ID]

… … … … … … … … …

B.3 Strength Allowables & Factors

Yield/ultimate at local metal temperature T(x): from Table B-1.

Knockdowns: [K\_T], [K\_surface], [K\_manufacturing] = [VALUES].

Allowables used in §6 tables reference: [ALLOWABLES\_DOC\_ID].

B.4 Fatigue Data & Methods

Infinite-life screen: Goodman with endurance limit σ\_e(T) = [VALUE] at [R=-1] (mean-corrected).

If screen exceeded, TLIFE (NASALIFE-based) parameters:

S–N: σ\_a^b · N = C(T); [b(T)], [C(T)] from [FATIGUE\_DB\_ID].

Mean stress correction: [Goodman / Gerber / Walker m=[…]].

Surface & notch: Kt=[…], q=[…], Kf = 1 + q( Kt − 1 ).

Miner’s rule accumulation across [RPM\_LIST or STEP] with [Δt or Δf].

Scatter factor on life: [SF\_LIFE]=[VALUE]; confidence: [CL]=[VALUE]%.

B.5 Thermal Dependence

Properties interpolated piecewise linearly vs. T; extrapolation beyond table bounds is not permitted (analysis clamps to nearest defined T).

B.6 Coatings / Liners

[COATING\_SPEC] modeled as [elastic/orthotropic], thickness [t], E(T) per [COATING\_PROP\_ID].

Residual stress not modeled in vibration loadcases (no thermal transients in §5.2–§5.5).

B.7 Traceability

Property sources and revisions: [MAT\_DB\_ID]/[REV], [FATIGUE\_DB\_ID]/[REV].

Any deviations recorded in §2.6 Data Quality Checks.

Figure B-1 Material Property Curves vs Temperature (E, σ\_y, σ\_u, α, ν) — [FIG\_B1\_ID] (Reserved)

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Appendix C — Engine Survey & Rig/Modal Test References (IDs / Revs)

C.1 Purpose

Records the minimal data pedigree for validation artifacts used in §4.4 and §6.5.

C.2 Engine Ground Vibration Survey (GVS)

Table C-1 Engine Survey & Rig/Modal Tests — IDs / Revs / Channels

Artefact ID / Rev Campaign Dates Units Processing Channels Used Notes

Engine Survey (GVS) [SURVEY\_IDS] [DATES] [accel g, displacement µm] [order tracking 1×, detrend, band-pass [FREQ\_RANGE]] [CH\_A, CH\_B, …] Used for Bode/Campbell overlay

CBO Run-Down Loads [CBO\_RD\_IDS] [DATES] [N, N·m] [RPM-align, resample Δt=[…]] [IFACE\_A, IFACE\_B] Consumed as-is per AMC E 520(c)(2)

CBO Run-On Loads [CBO\_RO\_IDS] [DATES] [N, N·m] [as above] [IFACE\_A, IFACE\_B]

Windmilling Loads [WINDMILL\_IDS] [DATES] [N, N·m] [1× envelope vs RPM] [IFACE\_A, IFACE\_B]

Limit OOB (1×) [LIM\_OOB\_IDS] [DATES] [N, N·m] [envelope vs RPM] [IFACE\_A, IFACE\_B]

Thermal Inputs [THERMAL\_IDS] [DATES] [°C, MPa] [steady] [HPCC nodesets] Pre-stress base

C.3 Sensor / Channel Locations (If Used)

Accelerometers at [HPCC measurement bosses / brackets]; coordinates in [FRAME\_A or GCS].

Orientation: [axis mapping].

Calibration: [CAL\_CERT\_ID], last date [DATE].

C.4 Processing Summary

Time–RPM alignment via [tach channel] with [order tracking algorithm].

Metrics used for correlation: amplitude [µm or g] and phase [deg] at 1× order.

Acceptance per §4.4: amplitude within [AMP\_TOL]%, phase within [PHASE\_TOL]°, frequency match within [FREQ\_TOL]%, MAC ≥ [MAC\_MIN] (if modal test used).

C.5 Validation Use

Overlay plots in §6.5: Figures 6-5a/b/c; summary in Table 6-6/6-7.

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Appendix D — Full MoC Matrix (Rule Text, Acceptance, Links)

D.1 Notes

This appendix expands §3.3–§3.5 with the full rule text and explicit acceptance basis. Rule text excerpts provided for traceability; authoritative source remains [REG\_BASIS\_DOC\_ID].

Table D-1 Full MoC Matrix (Rule Text / Acceptance / Evidence Links)

Rule Applicability to HPCC Rule Text (Excerpt) Compliance Approach (HPCC) Acceptance Basis Evidence / Links Status

CS-E 650 Yes (vibration surveys) [RULE\_TEXT\_SNIPPET] Use GVS to validate FE dynamic characteristics (1× amplitude/phase, Campbell crossings) §4.4; Fig. 6-5a/b/c; Tbl 6-6 [OK/Pending]

CS-E 810 Yes (blade failure) [RULE\_TEXT\_SNIPPET] Assess HPCC structural response during CBO run-down/run-on using Engine Dynamics validated loads Strength no-yield; fatigue limits per §2.5 §5.2/§5.3; Tbl 6-1/6-2/6-3 [OK/Pending]

CS-E 525 Yes (continued rotation) [RULE\_TEXT\_SNIPPET] Windmilling fatigue evaluation vs mission durations Miner’s rule; limits in §7 §5.4; Tbl 6-4; Tbl 7-4 [OK/Pending]

AMC E 520(c)(2) Yes (validated data) [RULE\_TEXT\_SNIPPET] Consume engine-level OOB loads “as validated” without re-derivation Data pedigree in §2.2/Appendix C Tbl 2-2; App C [OK/Pending]

[PROGRAM ALERT/VIB LIMIT DOC] Reference [RULE\_TEXT\_SNIPPET] Tie alert thresholds to maintenance actions §5.6; Tbl 5-6; §7 [OK/Pending]

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Appendix E — Informative (Non-Normative) — Imbalance Grades & Example Calculations (if included)

E.1 Purpose

Informative background on OOB force estimation and balance grades to aid interpretation of §5.5 and §6.4. Not part of the MoC.

E.2 Basic Relations (Synchronous 1×)

Eccentricity e [m] from residual unbalance U = m·e [kg·m] (mass m at radius e).

OOB force F₁×(ω) = U · ω² [N], where ω = 2π·RPM/60.

Interface moment may be approximated as M ≈ F · r\_eff for effective arm r\_eff = [VALUE] [m] (program-supplied in [LIM\_OOB\_IDS]).

E.3 Balance Grade (Informative)

If using ISO balance grade [ISO\_21940\_REF], permissible residual unbalance U\_per relates to grade G and rotor service speed ω\_s by U\_per = (9.55 × 10⁶ · G · m\_r)/RPM\_s [g·mm], where m\_r is rotor mass [kg] (units adjusted per reference).

Engine program provides the applied 1× envelope directly (no derivation here).

E.4 Worked Example (Placeholder)

Given [U\_applied]=[VALUE g·mm], at [RPM]=[VALUE], then

ω = 2π·[RPM]/60 = [VALUE] rad/s

F₁× = [U\_applied in kg·m] · ω² = [VALUE] N → mapped at [IFACE\_A]/[IFACE\_B] per §5.5.

Figure E-1 Balance-Grade Illustration (Informative) — [FIG\_E1\_ID] (Reserved)

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Appendix F — Responsibility & Interfaces (RACI)

F.1 RACI Summary (HPCC OOB Compliance)

Table F-1 Responsibility & Interfaces (RACI) — HPCC vs Engine Dynamics

Activity Engine Dynamics HPCC Structures (You) Materials Test/Instrumentation CVE/Compliance

Derive/validate engine OOB loadsets (CBO, windmill, limit) R/A C C C I

Provide frames, transforms, units, envelopes R/A C I I I

Build/validate HPCC FE model I R/A C C I

Apply loads, analyze thermal+OOB I R C I I

Correlate to GVS/modal data C R I C I

Strength/fatigue evaluation I R C I I

Define limitations/maintenance C R C I A

Certification documentation C R I I A

Legend: R=Responsible; A=Accountable; C=Consulted; I=Informed.

F.2 Interfaces

Data handover packages: per Table 2-2 and Appendix G (hash-locked).

Change control: any update to [CBO\_RD\_IDS], [CBO\_RO\_IDS], [WINDMILL\_IDS], [LIM\_OOB\_IDS], [THERMAL\_IDS] triggers §7 re-assessment.

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Appendix G — Data Packages & File Manifests (Hashes / Paths)

G.1 Purpose

Provides a manifest of inputs, models, and key outputs used to produce §5–§7 results. Files are immutable by SHA-256 hash.

G.2 Package Overview

Package Name: [PROGRAM\_CODE]-HPCC-OOB-[REV]

Owner: [OWNER\_NAME / ORG]

Date: [DATE]

Storage: [PATH/REPO/BUCKET]; Access: [LINK/VAULT\_ID]

G.3 Manifest

Table G-1 Data Packages & File Manifests (Hashes / Paths / Owners)

Item Role File Name & Path Rev SHA-256 Size Owner

Geometry Input [PATH]/[HPCC\_GEOM].agdb [REV] [HASH] [MB] [NAME]

FE Model (mesh) Input [PATH]/[HPCC\_FE].cdb [REV] [HASH] [MB] [NAME]

Solver Project Input [PATH]/[PROJECT].wbpj [REV] [HASH] [MB] [NAME]

Thermal Field Input [PATH]/[THERMAL\_FIELD].csv [REV] [HASH] [MB] [NAME]

CBO Run-Down Loads Input [PATH]/[CBO\_RD].csv [REV] [HASH] [MB] [Engine Dynamics]

CBO Run-On Loads Input [PATH]/[CBO\_RO].csv [REV] [HASH] [MB] [Engine Dynamics]

Windmilling Envelope Input [PATH]/[WINDMILL].csv [REV] [HASH] [MB] [Engine Dynamics]

Limit OOB 1× Input [PATH]/[LIM\_OOB].csv [REV] [HASH] [MB] [Engine Dynamics]

Damping Params Input [PATH]/[DAMPING].json [REV] [HASH] [kB] [Engine Dynamics]

Interfaces Map Input [PATH]/[INTERFACE\_IDS].xlsx [REV] [HASH] [kB] [NAME]

Analysis Script(s) Method [PATH]/[RUN\_SCRIPTS].py [REV] [HASH] [kB] [NAME]

Case Logs Evidence [PATH]/logs/[CASE\_ID].log [REV] [HASH] [kB] [NAME]

Strength Plots Evidence [PATH]/plots/[FIG\_6\_1a].png [REV] [HASH] [kB] [NAME]

Fatigue Tables Evidence [PATH]/tables/[TBL\_6\_4].xlsx [REV] [HASH] [kB] [NAME]

Correlation Plots Evidence [PATH]/plots/[FIG\_6\_5a].png [REV] [HASH] [kB] [NAME]

Report PDF Output [PATH]/[DOC\_ID]-[REV].pdf [REV] [HASH] [MB] [NAME]

G.4 Reproducibility Notes

Solver settings snapshot: Table 5-8; .param files at [PATH]/config/.

Random seeds (if any): [SEED\_VALUE or N/A].

Platform: [OS/CPU/RAM], solver build [VERSION].

G.5 Retention & Access

Retention per [DATA\_RETENTION\_POLICY\_ID]; access controlled by [ACL\_ID].

Any change to items in Table G-1 requires re-issue of this appendix with updated hashes.

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Cross-Appendix References

Mesh & contacts → Appendix A

Materials & allowables → Appendix B

Validation artefacts → Appendix C

Regulations & acceptance → Appendix D

Informative OOB background → Appendix E

RACI → Appendix F

File hashes & delivery → Appendix G

End of Appendices A–G.