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TTR/699 Software Reference

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Nomenclature

BDAS	Basic Data Acquisition System
CCW	Counter-Clockwise
CW	Clockwise
DAS	Data Acquisition System
DCMS	Drive Control Monitoring System
HPP	Half Peak-to-Peak
JVX	Joint Vertical Experimental proprotor
LRTA	Large Rotor Test Apparatus
NFAC	National Full-Scale Aerodynamics Complex
RDMS	Rotor Database Management System
SCR	Software Change Request
SOF	Safety of Flight
SofDAS	Safety of Flight Data Acquisition System
TCR	Test Change Request
TRAM	Tilt Rotor Aeroacoustic Model
TTR	Tiltrotor Test Rig
40x80	NFAC 40- by 80-ft Wind Tunnel

TTR/699 Software Reference

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A Introduction and Scope

A NASA research proprotor (Bell Model 699, a modified 609 rotor) was tested on the Tiltrotor Test Rig (TTR) in the National Full-Scale Aerodynamics Complex (NFAC) 40- by 80-Foot Wind Tunnel. This test constituted the checkout test of the TTR and the first wind-tunnel test of the 699 rotor. The objective was to demonstrate safe and efficient operation of the TTR under a wide variety of wind-tunnel conditions, including hover, conversion, and high-speed axial flow. See Reference 1 for details of the test, including physical characteristics of the TTR/699.

The measurements included 20 rotor blade strain gauges, 35 rotating rotor system measurements, 56 balance and torque tube strain gauges, and 41 TTR and wind tunnel parameters. Certain TTR health-monitoring data were recorded by the TTR Drive Control Monitory System (DCMS). The remainder of the data were acquired by the NFAC Data Acquisition System; see Ref. 2 for technical specifications. Reference 3 lists all data parameters acquired for TTR, including derived parameters, but does not contain details of associated data processing.

Inputs, constants, and equations required for computing TTR derived parameters are defined in the “TTR 699 Checkout Test NFAC Software Requirements Document” (Ref. 4). That document also includes safety monitoring limits. The present report is a redaction of the Requirements Document. The Software Reference retains the overall structure and nomenclature of the Requirements Document but is edited for readability. Safety-of-Flight (SOF) data are included and monitoring requirements are summarized, but derivation of such requirements is documented separately, principally in Bell reports.

This document begins with the definitions of constants and standard operating computations (Sections B and C). Rotor balance computations, with associated rotor performance coefficients, are given in Sections D through G. Axis definitions and tare corrections are discussed at the beginning of the first set of balance computations (Section D). Deprecated parameters are listed in Section E but not further described. Control angle calculations, hub loads, and spinner loads follow in Sections H through J.

Certain derived parameters are processed differently post-test (Section K) and real-time (Section L). The latter section includes monitoring limits. A few miscellaneous, non-standard parameters are collected in Section M. An appendix (Section N) includes suggestions for improvements.

Restrictions

This document, the Software Reference, has no restrictions on distribution, whereas the Software Requirements Document is restricted to U. S. government only.

Certain parameters are Bell proprietary and are so noted and omitted. Many load limits are derived from Bell design data, material specifications, or other proprietary sources; the associated table entries have been left blank. In contrast, nearly all computations needed for test data processing depend on the particulars of TTR instrumentation and NFAC operating conditions, which are not proprietary; the associated coefficients and scale factors are retained herein.

Proprietary documents are sometimes referenced for completeness, even though the data are available from unrestricted sources.

B Test Dependent Constants

Mathematical Constants

PI

Mathematical constant, rad
= 3.141593

DTR

Converts degrees to radians, rad/deg
= 0.017453293

RTD

Converts radians to degrees, deg/rad
= 57.29577951

Wind Tunnel Constants (Ref. 5)

CAT

Wind tunnel wall correction constant. (non-zero if using Prandtl-Glauert correction). Very approximate value pending definitive analysis (= 0.261 per Heyson, Ref. 6).
= 0.19

CROSS_SECTION_AREA

Wind tunnel cross-section area for the 40x80 with acoustic treatment, ft²
= 2754.59

CSP (0:3)

Correction coefficients for static plate
(in database)

CVPT (0:3)

Correction coefficients for reference ring pressure
(in database)

DH

Height from BARO transducer to tunnel centerline, ft
= 32.67

Model Rotor Constants

The following constants are model dependent. Actual values will be measured and recorded at the beginning of the test.

NPR

Data points per revolution
= 256

SamplesForMean

Number of samples to estimate mean values
= 422 (helicopter rpm)
= 500 (airplane rpm)

ROTRAD

Rotor radius, ft (per Bell Report 699-616-004 Vol. II, Ref. 7)
= 13.000

SIGMA

Rotor solidity, geometric (per Bell Report 699-616-004 Vol. II, Ref. 7)
= 0.0908

X_REF

Distance from rotor balance center to hub center (x-axis), ft
= 0.0
See Fig. 1 for axis system.

Y_REF

Distance from rotor balance center to hub center (y-axis), ft
= 0.0

Z_REF

Distance from rotor balance center to hub center (z-axis), ft
= 7.3085 ft (87.702 in) (per Bell dwg 699-616-005 Rev. A)

ALPHA1

Glauert area ratio (disk area / section area)
= $(\text{PI} * \text{ROTRAD}^2) / \text{CROSS_SECTION_AREA}$
= 0.192743

Rotor Control Displacement Calculation Constants

Most of these parameters are used in Section H. See Section D for a discussion of axis systems.

SIGNTABLE

T-frame orientation, looking from top, +1 for CCW, -1 for CW)
= -1

SIGNROT

Rotor rotation direction, looking from front, +1 for CCW, -1 for CW)
= +1

PARMS

Pitch arm blade station, in
(Bell Report 699-616-006 Vol. I, Ref. 8) *Bell proprietary*.

PARML

Pitch arm length, positive for distance in front of the blade leading edge, in
(Bell dwg. 699-616-525) *Bell proprietary*.

TORQL

Torque offset, positive when feathering axis is forward of center of rotation, in
Bell proprietary.

ACTRAD

Fixed actuator radius (all three the same), in
= 14.383 (per Bell dwg. 699-616-511, non-rotating swashplate)

RSPRAD

Rotating swashplate radius, in
= 10.897 (per Bell dwg. 699-616-510)

COLLN

Collective angle for actuator zero, deg
= 15 (pitch horns level)

PLL

Pitch link length, in
= 24.00 (per Bell Report 699-616-007 Rev. A, Section 1.7, Ref. 9)

PARAD

Pitch arm radius, pitch horns level, in
 $=\text{SQRT}(\text{PARMS}^2 + (\text{PARML} + \text{TORQL})^2)$
Bell proprietary.

PSIARM

Pitch arm geometry angle, deg
 $=\text{ATAN}((\text{PARML} + \text{TORQL}) / \text{PARMS}) * \text{RTD}$
Bell proprietary.
Pitch horn level (not adjusted for collective);
nominally = $-90 - \text{delta-3}$

PSICA

Swashplate angle, deg
= $-90 + \text{PSIARM}$
Bell proprietary.

PRAZ_A

Stationary Actuator A azimuth position, deg
= 90

PRAZ_B

Stationary Actuator B azimuth position, deg
= 210

PRAZ_C

Stationary Actuator C azimuth position, deg
= 330

PLAZ_1

Pitch link 1 azimuth position at swashplate relative to reference, deg
= PSIARM *Bell proprietary.*

Note: pitch links are rigged with 0-deg cant for pitch horns level,
So PLAZ_1 = PSIARM. Retain both constants for possible future use.

SSCAZ

Stationary Scissors azimuth position relative to reference, deg
= 30

SP_OFFSET

Offset between zero actuator reference and swashplate support tube gauges, in
= 13.07
Determined during the actuator calibration. (See also COLLN).

C_ACTLD

Correction for fixed actuator angle with respect to shaft at mid-stroke
= $\text{COS}(2.996^\circ) = 0.9986$

Hub Load Calculation Constants

These parameters are used in Section I. Numerical values are given in Section I.

LLO	Distance from lower gauges to hub center
LUP	Distance from upper gauges to hub center
LUP_B	Distance from upper gauges to hub center (backup)
CLOPL	Correction term for lower parallel gauge
CLOPR	Correction term for lower perpendicular gauge
CUPPL	Correction term for upper parallel gauge
CUPPR	Correction term for upper perpendicular gauge
CUPPL_B	Correction term for upper parallel gauge (backup)
CUPPR_B	Correction term for upper perpendicular gauge (backup)

Spinner Load Calculation Constants

These parameters are used in Section J. Numerical values are given in Section J.

AF_SPINNER	Spinner frontal area
AF_MASTMODULE	Mast module frontal area
UPR_BMA	Upper support beam-bending moment arm
UPR_RAD	Upper support effective radius

Strut Locations

These parameters are used in Section M. Numerical values are given in Section M.

STRUT_NXOFF	Nose strut longitudinal offset from balance center
STRUT_PXOFF	Port strut longitudinal offset from balance center
STRUT_PYOFF	Port strut lateral offset from centerline
STRUT_SYOFF	Starboard strut lateral offset from centerline
STRUT_ZOFF	Strut vertical offset from balance center (same for all struts)

C Tunnel Atmosphere and Model Operating Computations

Standard Tunnel Parameters

The following computations are shown using digital tunnel measurements. The digital measurements are updated once per rev but are stored at the nominal Basic Data Acquisition System (BDAS) data rate (256/rev). These calculations can also be done using analog measurements (set with a flag by the data system operator). These calculations should be NFAC standards; see Ref. 5.

The NFAC air data system was recalibrated in 2022, after the TTR/699 entry. As of this writing, no TTR/699 data have been updated to reflect the recalibration.

Inputs

PR_DIG	Reference Ring Pressure, psf
PSREF_DIG	Static Ring Pressure, psf
BARO_DIG	Barometric pressure in control room, psi
DH	Height from BARO transducer to tunnel centerline, ft
TTF_DIG	Tunnel Total Temperature, °F
HUM_DPT_DIG	Dew Point Temperature, °F

QU

Uncorrected dynamic pressure at ring locations, psf
 $= PR_DIG - PSREF_DIG$

DQSP

Static plate correction, psf
 $= f(QU, CSP)$ curve fit

QCLU

Uncorrected dynamic pressure at tunnel centerline, psf
 $= QU - DQSP$

PA

Atmospheric pressure at tunnel centerline, psfa
 $= BARO_DIG * 144 - (0.07285 * DH)$

DELPTR

Total pressure correction, psf
 $= f(QU, CVPT)$ curve fit

PT

Total pressure at tunnel centerline, psfa
 $= PA + PR_DIG + DELPTR$

PS

Static pressure at tunnel centerline, psfa
 $= PT - QCLU$

MTUN

Tunnel Mach number (This equation is exact for air and accounts for compressibility)

$$= \text{SQRT}(5 * ((\text{PT} / \text{PS})^{**}(2/7) - 1))$$

Q

Corrected tunnel dynamic pressure, psf number (Note: This equation is exact for air and accounts for compressibility)

$$= 0.7 * \text{PS} * \text{MTUN}^{**2}$$

TTR

Tunnel total temperature, °R

$$= \text{TTF_DIG} + 459.67$$

TSR

Tunnel static temperature, °R

$$= \text{TTR} / (1.0 + (1.0/5.0) * \text{MTUN}^{**2})$$

TSF

Tunnel static temperature, °F

$$= \text{TSR} - 459.67$$

VPDP

Test section dew point vapor pressure, psf

$$= (2.0901 + 3.46\text{e-}6 * \text{PA}) * 6.1121 * \exp((17.502 * \text{HUM_DPT_DIG} - 560.064) / (401.62 + \text{HUM_DPT_DIG}))$$

VPDB

Test section dry bulb vapor pressure, psf

$$= (2.0901 + 3.46\text{e-}6 * \text{PA}) * 6.1121 * \exp((17.502 * \text{TSF} - 560.064) / (401.62 + \text{TSF}))$$

RH

Test section relative humidity, %

$$= \text{VPDP} / \text{VPDB} * 100$$

RHO

Air density, slug/ft³

$$= 0.000582560 * (\text{PS} - (0.38 * \text{VPDP})) / \text{TSR}$$

VFPS

Tunnel speed, ft/sec

$$= \text{SQRT}(2.0 * \text{Q} / \text{RHO})$$

VKTS

Tunnel speed, kts

$$= \text{VFPS} * 0.5925$$

VISC

Tunnel air viscosity, slug/ft-sec

$$= 2.27\text{e-}8 * (\text{TSR}^{**1.5} / (\text{TSR} + 198.6))$$

REYN

Reynolds number, millions per foot
 $= (\text{RHO} * \text{VFPS} / \text{VISC}) / 1.0\text{e}+06$

CSND

Tunnel speed of sound, ft/sec
 $= 49.0223 * \text{SQRT}(\text{TSR})$

Rotor Operating Parameters

The required yaw angle is that of the T-frame, not the turntable. The data come from different sources on the Model Support System and are consolidated into a single parameter “TT_YAW”. The TTR is mounted backwards on the T-frame, so the yaw angle is 180 deg from the traditional usage. The sign convention is that TTR helicopter mode is +90 deg yaw clockwise from airplane mode. See Section D for a discussion of axis systems.

Inputs

TT_YAW	Yaw angle, deg, positive CW from above, 0 deg pointing upstream (TTR airplane mode)
RPM	Rotor rotation rate, rev/min

OMR

Rotor tip speed, ft/sec
 $= \text{RPM} * \text{PI} * \text{ROTRAD} / 30.0$

MTIP

Hover tip Mach number
 $= \text{OMR} / \text{CSND}$

MU

Rotor advance ratio (pure helicopter mode)
 $= \text{VFPS} / \text{OMR}$
 Note: Many publications define the rotor advance ratio as
 $\text{VFPS} * \text{COS}(\text{ALPHA} * \text{DTR}) / \text{OMR}$

MUX

In-plane advance ratio (helicopter mode)
 $= \text{VFPS} * \text{ABS}(\text{COS}(\text{ALPHA} * \text{DTR})) / \text{OMR}$

MUY

Lateral advance ratio
 (not used for TTR; set=0)

MUZ

Axial advance ratio (airplane mode)
 $= \text{VFPS} * \text{ABS}(\text{SIN}(\text{ALPHA} * \text{DTR})) / \text{OMR}$

MUAT

Rotor advancing tip advance ratio
 $= \text{SQRT}((1 + \text{MUX})**2 + \text{MUZ}**2)$

MAT

Rotor advancing tip Mach number
= $MTIP * MUAT$

TT_YAW_C

Corrected yaw angle
= $(1 - (0.3/90.3)) * TT_YAW$

ALPHA

Shaft tilt in wind tunnel axes, positive clockwise looking down, deg
-90 deg is with the shaft pointing upstream.
= $TT_YAW_C - 90$

Normalization Constants**CONSTF**

Normalization constant for force parameters, lb
= $RHO * (PI * ROTRAD**2) * OMR**2$

CONSTM

Normalization constant for moment parameters, ft-lb
= $CONSTF * ROTRAD$

CONSTP

Normalization constant for power parameters, ft-lb/s
= $CONSTF * OMR$

Model State

It is possible to operate the TTR in several different configurations of both the rig and the wind tunnel. For the sake of a complete database, several data flags are defined to indicate the exact configuration for each data point.

As of this writing, IROTOR and IMOTORxx have not been fully implemented in the database.

IROTOR

Rotor configuration
0=no rotor, 1=rotor, 2=hub only
Configuration #2 was used only once and is not so noted in the database.

IMOTORFP

TTR Forward Port motor status
0=not powered, 1=powered

IMOTOREFS

TTR Forward Starboard motor status
0=not powered, 1=powered

IMOTORAP

TTR Aft Port motor status
0=not powered, 1=powered

IMOTORAS

TTR Aft Starboard motor status
0=not powered, 1=powered

Data Identifiers

The following data point identifiers are automatically generated.

Time (six values)

Year/month/day/hrs/min/sec

Run

Run number [integer]

Point

Point number [integer]

D Rotor Balance Data Reduction, Overview

Four sets of balance equations, or “balances,” each applied to two sets of strain gauge measurements, are defined for TTR. The “B1” and “B2” equations derive forces and moments directly from individual balance gauge voltages. Two different sets of equations are also provided which use traditional balance equations based on combined gauge voltages. Here, voltages are added or subtracted as appropriate for forces and moments before calibration coefficients are derived. These traditional equations (AIAA recommended) for the primary and secondary gauges are labeled “B3” and “B4”. Note that balances B1 and B2 are not to be confused with primary and secondary strain gauges.

The B1 and B2 balances proved more susceptible to thermal drift than B3 and B4. Many B1 and B2 parameters are stored in the RDMS database, but are intended for diagnostic purposes only and should not normally be used for research. They are not documented in detail herein. A further set, B5, is briefly described below.

The complete balance equations are documented separately (Meyn, Ref. 10; see also Ref. 11). The present document describes the general procedure, including axis transformations and tare corrections. Axis transformations to the rotor hub and conversion to rotor performance coefficients are identical for all balances. The following descriptive matter applies to all computations.

Table 1 lists the strain gauges that provide data to the balance computations. AF, NF, and SF gauges are on the balance posts; FC gauges are on the torque tube flex coupling.

Table 1. Balance and torque tube strain gauges

Strain gauge readings (voltages)	
Primary	Secondary
AF000_B1	AF000_B2
AF090_B1	AF090_B2
AF180_B1	AF180_B2
AF270_B1	AF270_B2
NF000_B1	NF000_B2
NF090_B1	NF090_B2
NF180_B1	NF180_B2
NF270_B1	NF270_B2
SF000_B1	SF000_B2
SF090_B1	SF090_B2
SF180_B1	SF180_B2
SF270_B1	SF270_B2
FCTH_B1	FCTH_B2
FCTQ_B1	FCTQ_B2

The NF180_B1 primary gauge tends to drift, which yields unrealistic normal force loads. Therefore, the secondary gauge NF180_B2 is used for B3 computations. A fifth balance B5 is defined that is the same as B3 but uses NF180_B1. B5 is otherwise identical to B3 and is intended for diagnostic purposes, therefore B5 is not further documented herein.

The parameters defined for TTR match the Large Rotor Test Apparatus (LRTA) UH-60 parameters (Ref. 12) wherever possible. However, the LRTA balance is vertical, whereas the TTR balance is horizontal and its axes vary with the T-frame yaw angle. Certain parameters, usually pitch and yaw, must be swapped for geometric consistency.

Safety of Flight (SOF) computations use a highly simplified set of balance equations, intended for rapid and robust numerics. See Section L for details.

Axis Definitions

A brief overview of the various axis systems and measurements is given here.

Historical Note: The coordinate system used for the LRTA UH-60 test is not the same as that used for the JVX rotor tests, and neither system is the same as that used for the TTR balance calibration. The UH-60 and TRAM rotors moved in pitch, not yaw. It is therefore impossible for TTR parameters to consistently match UH-60, JVX or TRAM rotor test parameters without further conversions not included here.

TTR cannot simultaneously match the traditional helicopter and airplane conventions for angle of attack (rotor shaft $\alpha=0$ deg is +90 deg airplane nose up). The helicopter convention is used here because it is relevant for rotor loads throughout conversion mode; it also maximizes reuse of software.

For the TTR/699, there are three relevant axis systems: the balance axes (Fig. 1) and the rotor shaft (or mast) axes (Figs 2), and rotating blade axes (Fig. 3). Total rotor and control system loads are measured in the balance axis system and must be transferred to the shaft axis system to get rotor loads at the hub center. Pitch-link loads must also be transferred to shaft axes to get total rotating hub loads. The rotor loads must be converted to aircraft axes (699-616-004 Vol. I, Ref. 7) to compare with flight loads. Note that SOF limits are defined in rotor shaft axes.

TTR uses the Bell 699 rotor (a modified right-hand 609 rotor), with the nacelle pivot axis rotated to align with the NFAC T-frame axis of rotation. As such, it should match the Bell convention for a right-hand rotor (Ref. 7), but the sense of rotation is reversed, looking along the nacelle pivot.

Warning: Bell used different axis systems in different documents. E.g., TTR body axes in 699-616-900 (Ref. 13) are not the same as the rotor axes in 699-616-004 (Ref. 7). Note also that torque, roll and yaw (Q, RM, YM) are negative for a right-handed coordinate system.

Table 2. TTR rotor balance sign convention (right-hand rotor for TTR)

Axis	0° yaw	90° yaw
NF	forward*	right
AF	right	aft†
SF	down	down
YM	opposite to rotation	opposite to rotation
PM	nose right	nose right
RM	nose down	nose down

* upstream

† downstream

Torque (TQ) is measured by the torque tube. The flex coupling measures residual shaft thrust (TH) not measured by the balance.

The aircraft mast axes rotate about the horizontal axis as the aircraft converts to airplane mode. In contrast, the TTR balance axes rotate with the 40x80 T-frame about the vertical axis, perpendicular to the mast; only SF and PM remain unchanged with respect to free space.

In the wind axis system, the angle of attack of the rotor plane with respect to the airflow varies with T-frame yaw. In wind-tunnel convention, 0° shaft tilt (helicopter mode) is defined with the rotor shaft perpendicular to the flow, and the shaft tilt angle in airplane mode is -90°. Hence the TTR shaft angle is offset 90° from the airplane nacelle tilt convention, and the pivot axis is vertical, not horizontal. Table 3 summarizes the relations between axis systems. The definitions used here minimize the conversions between balance measurements, flow measurements, and rotor loads.

Table 3. Airplane vs. TTR shaft angle

Airplane convention	T-frame	TTR
0° nacelle tilt	0° yaw	-90° shaft angle
90° nacelle tilt	90° yaw	0° shaft angle

With a horizontal rotor shaft and the above axis convention, the usage of traditional wind-axis loads changes to the following (compare WN-06-005v2, Ref. 11):

Table 4. TTR wind-axis sign convention

Parameter	Load	Polarity
DRAG,W_Bn	drag	positive aft
SIDE,W_Bn	side force	positive down
LIFT,W_Bn	lift	positive to right
ROLL,W_Bn	roll moment	positive right side down
PITCH,W_Bn	pitch moment	positive right side aft
YAW,W_Bn	yaw moment	positive nose down

With these definitions, the standard equations for wall-effect corrections can be used unchanged, given an appropriate Glauert correction constant (CAT).

In the rotating system, zero azimuth is defined with the red blade horizontal, pointing to the right when looking forward, hence aligned with the 0° balance post (Fig. 2). Zero azimuth is aligned with the master spline on the rotor mast. The swashplate driver is approximately aligned opposite the white blade pitch link (Bell dwg. 699-616-500). Figure 3 shows the blade color convention, flapping axes and related parameters.

Looking aft in airplane mode

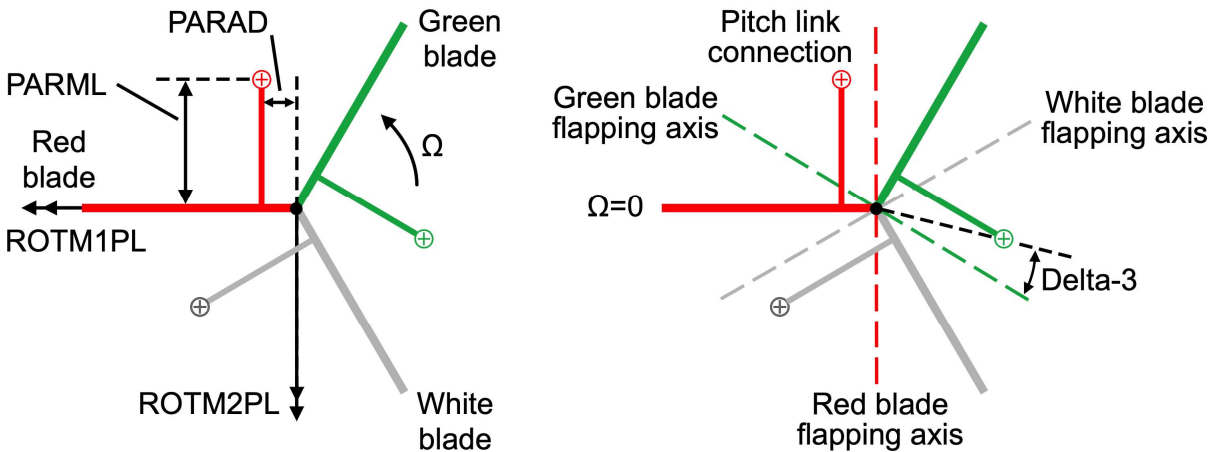


Fig. 3. Rotor hub schematic and blade orientation (ref. Bell drawing 699-616-527).

Tare Correction Roadmap

The following paragraphs describe the formal weight tare correction process. In practice, the data were sufficiently linear that nearly all weight tares were corrected during the instrumentation zero calibrations. The major exceptions were moments dependent on swashplate position. The complete roadmap is described below for reference, but see Sections F and G for the simplified computations actually used.

TTR yaws with the T-frame, but does not pitch, so the weight tares should not change with yaw angle. However, this assumption will be experimentally checked and yaw corrections will be retained in case they are needed.

Figure 4 shows the swashplate assembly on the support tube. The weight of the swashplate creates side force and roll moment tares (and possibly pitching moment tares, which should be negligible). The side force caused by swashplate weight is constant, therefore it is included in the weight tare. The equivalent roll moment varies with swashplate position; the needed tare correction is determined as a function of collective as part of the control console calibration.

Strain gauges on the support tube measure the swashplate-induced moments, but the data are intended only for diagnostics and are not applied to the balance loads.

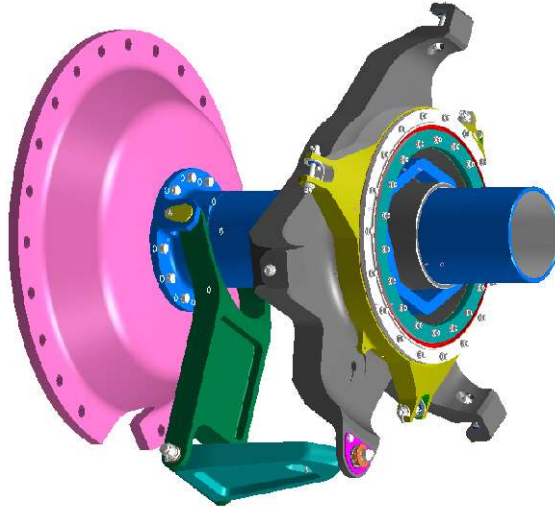


Fig. 4. Swashplate assembly and anti-drive link on support tube (Ref. 9, Section 1.3).

Weight tares will be different with the rotor on and off. The swashplate position will be fixed for spinner tare runs, so rotor-off swashplate weight tares will be constants.

Swashplate weight *tares* are mixed in with measured control *loads*, and the balance equations and rotor loads calculations must obey the distinction.

TTR will need at least three different sets of rotor force and moment calculations: “raw” rotor balance loads, rotor loads corrected by spinner *tares*, and rotor loads corrected by *measured* spinner forces. It is assumed that the last of these will not be available for real-time monitoring.

Of the many possible configurations of hub, blades, and spinner, only two are planned for testing: no hub or blades, but spinner cover plates installed; and hub with blades and spinner, but no cover plates. Thus, there are two sets of weight tares. There are no plans to acquire research data with the hub installed without blades (a single diagnostic run was performed in that configuration).

The equations below provide a general overview of the calculations used to compute balance forces and moments. Detailed equations/procedures are available from the NFAC DAS team. Note that the subtraction of weight tare and aerodynamic tares from the uncorrected rotor balance loads is performed in the *balance axis system*. For the NFAC DAS, the weight and aero tare files are identified in the NFAC setup file.

A roadmap for the application of the tares is provided below:

$$WT = \text{Weight Tare} = f(\Psi, \Theta_c)$$

$$AT = \text{Aerodynamic Tare} = f(\Psi, Q, V)$$

Where Ψ = shaft angle = angle of attack, Θ_c = collective pitch angle, Q = dynamic pressure, and V = tunnel velocity.

Positive directions are defined with the rotor facing upstream.

FOR HOVER (VKTS < 5 kts):

Corrected Data = Uncorrected Balance Data – WT[with rotor, non-rotating]

Note: There is no WT for flex coupling torque

FOR FORWARD FLIGHT (VKTS ≥ 5 kts)

Corrected Data = Uncorrected Balance Data – WT[with rotor, non-rotating]
– AT[w/o rotor, with rotation]

Notes:

- 1) Weight Tare (WT) accounts for changes on the rotor balance due to the effects of model angle-of-attack (T-frame position). This correction should be nearly constant for TTR.
- 2) Aerodynamic Tare (AT) accounts for load changes on the rotor balance due to the effects of wind-on aerodynamics at various model angles-of-attack (T-frame positions).
- 3) WT (hub without rotor, non-rotating) is subtracted from the Aerodynamic Tare prior to curve fit to avoid counting the effect of model weight twice.
- 4) The weight of the swashplate creates a roll moment on the balance, which is measured by strain gauges on the support tube and is subtracted from the measured balance moment.
- 5) Dead weight (constant weight) is accounted for by pre- and post-run zero calcs.

Rotor Balance Aerodynamic Tares

Aerodynamic tares are obtained with wind on, spinner with cover plates installed, and hub and blades off. Data from specific runs were analyzed to obtain the curve fit/tare coefficients as functions of shaft angle Ψ and tunnel Q or V. The data used to determine aero tares were corrected for rotor off weight tares and thermal drift. Values are in the balance axis system.

Tares are defined only in the range $0 \leq \Psi \leq 110$ deg and are set to zero elsewhere, including reverse flow. See Ref. 14 for derivations.

The spinner aerodynamic tare parameters are common to all balances, so they are calculated outside of the computational flow described in Sections F and G.

AFATR

Tare with rotating spinner for balance axial force (positive starboard), lb

```

IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN
  AFATR = 0.0
ELSE IF (TT_YAW_C ≤ 90) THEN
  AFATR = -2.26E-05 * Q * (TT_YAW_C)**3 + 1.40E-03 * Q *
  (TT_YAW_C)**2 + 0.140 * Q * (TT_YAW_C)
ELSE
  AFATR = 8.49E-03 * Q * (TT_YAW_C)**2 - 1.81 * Q *
  (TT_YAW_C) + 99.3 * Q
ENDIF
ENDIF

```

NFATR

Tare with rotating spinner for balance normal force (positive forward), lb

```

IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN
  NFATR = 0.0
ELSE IF (TT_YAW_C < 15) THEN
  NFATR = -0.833 * Q
ELSE IF (TT_YAW_C ≤ 90) THEN
  NFATR = -2.21E-05 * Q * (TT_YAW_C)**3 + 3.79E-03 * Q *
  (TT_YAW_C)**2 - 0.0947 * Q * (TT_YAW_C) - 10.41
ELSE
  NFATR = -8.64E-04 * Q * (TT_YAW_C)**2 + 0.108 * Q *
  (TT_YAW_C) + 27.7
ENDIF
ENDIF

```

SFATR

Tare with rotating spinner for balance side force (positive down), lb

```

IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN
  SFATR = 0.0
ELSE IF (TT_YAW_C < 90) THEN
  SFATR = -31.5 * VKTS * N(TT_YAW_C; 76.3, 8.96)
ELSE
  SFATR = -2.65E-03 * VKTS * (TT_YAW_C)**2 + 0.515 * VKTS *
  (TT_YAW_C) - VKTS * 26.1
ENDIF
ENDIF

```

where $N(x; \mu, \sigma)$ is the probability density function with normal distribution, $\mu = 76.3$ deg, $\sigma = 8.96$ deg, and scale factor = -31.5 . Note that SFATR depends upon V (knots), not Q (lb/ft²). $N(x; \mu, \sigma)$ is used merely for computational convenience; it has no physical significance.

PMATR

Tare with rotating spinner for balance pitching moment (positive nose right), ft-lb

```
IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN
  PMATR = 0.0
ELSE IF (TT_YAW_C ≤ 90) THEN
  PMATR = -1.38E-04 * Q * (TT_YAW_C)**3 + 2.11E-03 * Q *
  (TT_YAW_C)**2 + 1.54 * Q * (TT_YAW_C) - 3.18 * Q
ELSE
  PMATR = 6.00E-02 * Q * (TT_YAW_C)**2 - 13.0 * Q *
  (TT_YAW_C) + 719 * Q
ENDIF
ENDIF
```

RMATR

Tare with rotating spinner for balance rolling moment (positive nose down), ft-lb

```
IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN
  RMATR = 0.0
ELSE IF (TT_YAW_C < 90) THEN
  RMATR = -277 * VKTS * N(TT_YAW_C; 76.1, 9.99)
ELSE
  RMATR = -1.71E-02 * VKTS * (TT_YAW_C)**2 + 3.36 * VKTS *
  (TT_YAW_C) - 175 * VKTS
ENDIF
ENDIF
```

where $N(x; \mu, \sigma)$ is the probability density function with normal distribution, $\mu = 76.1$ deg, $\sigma = 9.99$ deg, and scale factor = -277. Note that PMATR depends upon V (knots), not Q (lb/ft²). $N(x; \mu, \sigma)$ is used merely for computational convenience; it has no physical significance.

TQATR

Aerodynamic tare with rotating spinner for flex-coupling torque,
(positive clockwise looking towards balance), ft-lb.

= 0

CPOS_ID_B1
CPOS_NI_B1
CPOS_NI_B1
CPOSID_B1_ME
CPOSID_B1_ME
CPOSNI_B1_ME
CPOSNI_B1_ME
CPRAT_B1
CPRAT_B1
CPRAT_B1_ME
CPRAT_B1_ME
CT_B1
CTOS_B1
CX_B1
CXOS_B1
CYR_BD_B1
CYR_W_B1
CYR_WE_B1
CYROS_BD_B1
CYROS_W_B1
CYROS_WE_B1
DALPHA_B1
DEQ_B1
DEQ_B1_ME
DRAG_W_B1
DRAG_WE_B1
ETAP_B1
ETAP_B1_ME
ETAP_GC_B1
ETAP_GC_B1_ME
FCTH_CB_B1
FCTH_CI_B1
FCTH_EU_B1
FCTH_V_B1
FCTQ_CB_B1
FCTQ_CI_B1
FCTQ_EU_B1
FCTQ_V_B1
FE_B1
FE_B1_ME
FMERIT_B1
FMERIT_B1_ME
HFORCE_B1
HP_B1
LIFT_W_B1
LIFT_WE_B1
LOD_B1
LOD_B1_ME
MUZ_GC_B1
MUZ_GC_B1_ME
NF_BAL_B1
NF_BD_B1
NF_CB_B1
NF_CI_B1
NF_CWT_B1
NF_EU_B1

CPOS_ID_B2
CPOS_NI_B2
CPOS_NI_B2
CPOSID_B2_ME
CPOSID_B2_ME
CPOSNI_B2_ME
CPOSNI_B2_ME
CPRAT_B2
CPRAT_B2
CPRAT_B2_ME
CPRAT_B2_ME
CT_B2
CTOS_B2
CX_B2
CXOS_B2
CYR_BD_B2
CYR_W_B2
CYR_WE_B2
CYROS_BD_B2
CYROS_W_B2
CYROS_WE_B2
DALPHA_B2
DEQ_B2
DEQ_B2_ME
DRAG_W_B2
DRAG_WE_B2
ETAP_B2
ETAP_B2_ME
ETAP_GC_B2
ETAP_GC_B2_ME
FCTH_CB_B2
FCTH_CI_B2
FCTH_EU_B2
FCTH_V_B2
FCTQ_CB_B2
FCTQ_CI_B2
FCTQ_EU_B2
FCTQ_V_B2
FE_B2
FE_B2_ME
FMERIT_B2
FMERIT_B2_ME
HFORCE_B2
HP_B2
LIFT_W_B2
LIFT_WE_B2
LOD_B2
LOD_B2_ME
MUZ_GC_B2
MUZ_GC_B2_ME
NF_BAL_B2
NF_BD_B2
NF_CB_B2
NF_CI_B2
NF_CWT_B2
NF_EU_B2

CPOS_ID_B5
CPOS_NI_B5
CPOS_NI_B5
CPOSID_B5_ME
CPOSID_B5_ME
CPOSNI_B5_ME
CPOSNI_B5_ME
CPRAT_B5
CPRAT_B5
CPRAT_B5_ME
CPRAT_B5_ME
CT_B5
CTOS_B5
CX_B5
CXOS_B5
CYR_BD_B5
CYR_W_B5
CYR_WE_B5
CYROS_BD_B5
CYROS_W_B5
CYROS_WE_B5
DALPHA_B5
DEQ_B5
DEQ_B5_ME
DRAG_W_B5
DRAG_WE_B5
ETAP_B5
ETAP_B5_ME
ETAP_GC_B5
ETAP_GC_B5_ME
FCTH_CB_B5
FCTH_CI_B5
FCTH_EU_B5
FCTH_V_B5
FCTQ_CB_B5
FCTQ_CI_B5
FCTQ_EU_B5
FCTQ_V_B5
FE_B5
FE_B5_ME
FMERIT_B5
FMERIT_B5_ME
HFORCE_B5
HP_B5
LIFT_W_B5
LIFT_WE_B5
LOD_B5
LOD_B5_ME
MUZ_GC_B5
MUZ_GC_B5_ME
NF_BAL_B5
NF_BD_B5
NF_CB_B5
NF_CI_B5
NF_CWT_B5
NF_EU_B5

NF_UNC_B1
NF_V_B1
NFWTNRB_B1
PITCH_W_B1
PITCH_WE_B1
PM_BAL_B1
PM_BD_B1
PM_CB_B1
PM_CI_B1
PM_CWT_B1
PM_EU_B1
PM_UNC_B1
PM_V_B1
PMWTNRB_B1
RM_BAL_B1
RM_BD_B1
RM_CB_B1
RM_CI_B1
RM_CWT_B1
RM_EU_B1
RM_UNC_B1
RM_V_B1
RMWTNRB_B1
ROLL_W_B1
ROLL_WE_B1
SF_BAL_B1
SF_BD_B1
SF_CB_B1
SF_CI_B1
SF_CWT_B1
SF_EU_B1
SF_UNC_B1
SF_V_B1
SFWTNRB_B1
SIDE_W_B1
SIDE_WE_B1
THRUST_B1
TORQ_B1
TQWTNRB_B1
VOVH_B1
VOVH_B1_ME
VPOV_B1
VPOV_B1_ME
XFORCE_B1
YAW_W_B1
YAW_WE_B1
YFORCE_B1
YM_BAL_B1
YM_BD_B1
YM_CB_B1
YM_CI_B1
YM_CWT_B1
YM_EU_B1
YM_UNC_B1
YM_V_B1

NF_UNC_B2
NF_V_B2
NFWTNRB_B2
PITCH_W_B2
PITCH_WE_B2
PM_BAL_B2
PM_BD_B2
PM_CB_B2
PM_CI_B2
PM_CWT_B2
PM_EU_B2
PM_UNC_B2
PM_V_B2
PMWTNRB_B2
RM_BAL_B2
RM_BD_B2
RM_CB_B2
RM_CI_B2
RM_CWT_B2
RM_EU_B2
RM_UNC_B2
RM_V_B2
RMWTNRB_B2
ROLL_W_B2
ROLL_WE_B2
SF_BAL_B2
SF_BD_B2
SF_CB_B2
SF_CI_B2
SF_CWT_B2
SF_EU_B2
SF_UNC_B2
SF_V_B2
SFWTNRB_B2
SIDE_W_B2
SIDE_WE_B2
THRUST_B2
TORQ_B2
TQWTNRB_B2
VOVH_B2
VOVH_B2_ME
VPOV_B2
VPOV_B2_ME
XFORCE_B2
YAW_W_B2
YAW_WE_B2
YFORCE_B2
YM_BAL_B2
YM_BD_B2
YM_CB_B2
YM_CI_B2
YM_CWT_B2
YM_EU_B2
YM_UNC_B2
YM_V_B2

NF_UNC_B5
NF_V_B5
NFWTNRB_B5
PITCH_W_B5
PITCH_WE_B5
PM_BAL_B5
PM_BD_B5
PM_CB_B5
PM_CI_B5
PM_CWT_B5
PM_EU_B5
PM_UNC_B5
PM_V_B5
PMWTNRB_B5
RM_BAL_B5
RM_BD_B5
RM_CB_B5
RM_CI_B5
RM_CWT_B5
RM_EU_B5
RM_UNC_B5
RM_V_B5
RMWTNRB_B5
ROLL_W_B5
ROLL_WE_B5
SF_BAL_B5
SF_BD_B5
SF_CB_B5
SF_CI_B5
SF_CWT_B5
SF_EU_B5
SF_UNC_B5
SF_V_B5
SFWTNRB_B5
SIDE_W_B5
SIDE_WE_B5
THRUST_B5
TORQ_B5
TQWTNRB_B5
VOVH_B5
VOVH_B5_ME
VPOV_B5
VPOV_B5_ME
XFORCE_B5
YAW_W_B5
YAW_WE_B5
YFORCE_B5
YM_BAL_B5
YM_BD_B5
YM_CB_B5
YM_CI_B5
YM_CWT_B5
YM_EU_B5
YM_UNC_B5
YM_V_B5

F Rotor Balance Data Reduction, Primary Gauge Set (B3)

The suffix “_B3” is used to denote the traditional load calculations using the Primary balance gauge set, and “_B4” for the traditional load calculations using the Secondary gauge set (Ref. 10). However, the NF180_B1 primary gauge tends to drift, which yields unrealistic normal force loads. Therefore, the secondary gauge NF180_B2 is used for B3 computations. A fifth balance B5 is defined that is the same as B3 but uses NF180_B1. B5 is otherwise identical to B3 and is intended for diagnostic purposes, therefore B5 is not further documented herein.

Weight Tare Corrections (B3)

Weight Tares with Non-rotating Spinner (Rotor Off), Primary Gauge Set (B3)

These weight tares are obtained with wind off, non-rotating spinner with cover plates installed, and hub and blades off. Data from specific runs are analyzed to obtain the curve fit/tare coefficients. These data are curve-fit as functions of shaft angle (T-frame angle). The curve fits were determined after installation into the test section.

These parameters are not normally stored, but are shown here to clarify the process.

NFWTNSP_B3

Weight tare with nonrotating spinner for balance normal force (positive forward), lb
= 0

AFWTNSP_B3

Weight tare with nonrotating spinner for balance axial force (positive starboard), lb
= 0

SFWTNSP_B3

Weight tare with nonrotating spinner for balance side force (positive down), lb
= 0

PMWTNSP_B3

Weight tare with nonrotating spinner for balance pitching moment (positive nose right), ft-lb
= 0

RMWTNSP_B3

Weight tare with nonrotating spinner for balance rolling moment (positive nose down), ft-lb
= RMWTNRB

Effectively = 0 with the rotor off and the swashplate in fixed position.

TQWTNSP_B3

Weight tare with nonrotating spinner for flex-coupling torque,
(positive clockwise looking towards balance), ft-lb
= 0

Weight Tares with Non-rotating Rotor (Spinner On), Primary Gauge Set (B3)

These weight tares are obtained with wind off, non-rotating hub, and blades on. Data from

specific runs are analyzed to obtain the curve fit/tare coefficients. These data are curve-fit as functions of shaft angle and swashplate position. The curve fits were determined after installation into the test section; only the RM variation with swashplate position is non-zero. There was no significant difference between balances, so the distinction is here dropped.

These parameters are not normally stored, but are shown here to clarify the process.

NFWTNRB_B3

Weight tare with nonrotating blade for balance normal force (positive forward), lb
= 0

AFWTNRB_B3

Weight tare with nonrotating blade for balance axial force (positive starboard), lb
= 0

SFWTNRB_B3

Weight tare with nonrotating blade for balance side force (positive down), lb
= 0

PMWTNRB_B3

Weight tare with nonrotating blade for balance pitching moment (positive nose right),
ft-lb
= 0

RMWTNRB_B3

Weight tare with nonrotating blade for balance rolling moment (positive nose down),
ft-lb

$$RMWTNRB_B3 = 18.0 * SPCOLL$$

Stored as RMWTNRB because there is no physical difference between _B3 and _B4.

TQWTNRB_B3

Weight tare with nonrotating blade for flex-coupling torque,
(positive clockwise looking towards balance), ft-lb
= 0

Balance Load Calculations (B3)

Uncorrected Load Gauge Readings (Balance Axis), Primary Gauge Set (B3)

Combine RCAL corrected measurements into load gauge readings (V) in the balance axis system. Note the suffix “_B3” for Primary balance gauge set. These measurements are determined by multiplying the 14 individual primary balance and flex-coupling gauge voltages by the matrix [SL_B3]; the [SL_B3] matrix is the same as used in the LRTA data reduction (Ref. 12). See also Equivalent Parameters, below.

SL_B3

Balance gauge voltages to load gauge (calibration) voltages matrix (Eqns. 8-10, WN-99-021, Ref. 15). This matrix is the same for the B3 and B4 balance computations.

$$= \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

NF_V_B3

Load readings for normal force (positive forward), V

AF_V_B3

Load readings for axial force (positive starboard), V

SF_V_B3

Load readings for side force (positive down), V

PM_V_B3

Load readings for pitching moment (positive nose right), V

RM_V_B3

Load readings for rolling moment (positive nose down), V

YM_V_B3

Load readings for yaw moment (positive clockwise looking towards balance), V

FCTH_V_B3

Load readings for flex-coupling thrust (positive forward), V

FCTQ_V_B3

Load readings for flex-coupling torque,
(positive clockwise looking towards balance), V

Uncorrected Balance Loads (Balance Axis), Primary Gauge Set (B3)

Convert load gauges to uncorrected loads in engineering units (EU) expressed in the balance axis system. Note the suffix “_B3” for Primary balance gauge set. These are determined by multiplying the eight uncorrected load gauge readings by the matrix [D1]; the [D1] matrix is unique for this set of gauges.

D1_B3

First order calibration matrix. (Eqn. 11, WN-99-021, Ref. 15)
This matrix is provided as a text file.

NF_EU_B3

Uncorrected normal force (positive forward), lb

AF_EU_B3

Uncorrected axial force (positive starboard), lb

SF_EU_B3

Uncorrected side force (positive down), lb

PM_EU_B3

Uncorrected pitching moment (positive nose right), ft-lb

RM_EU_B3

Uncorrected rolling moment (positive nose down), ft-lb

YM_EU_B3

Uncorrected yaw moment (positive clockwise looking towards balance), ft-lb

FCTH_EU_B3

Uncorrected flex-coupling thrust (positive forward), lb

FCTQ_EU_B3

Uncorrected flex-coupling torque (positive clockwise looking towards balance), ft-lb

Corrected Loads for Non-linear Interactions (Balance Axis), Primary Gauge Set (B3)

Next, the load-gauge engineering unit data above (XX_EU_B3) are corrected for non-linear model terms for gauge interactions and cross-component loading. Note the suffix “_B3” for Primary balance gauge set. These are determined by multiplying the eight uncorrected balance loads by the matrix [D2]. For the NFAC DAS balance load calculations, only linear terms will be used, so the [D2] matrix is all zeros, which means the corrected balance loads are the same as the uncorrected balance loads.

D2_B3

Second order calibration matrix. (Eqn. 12a, WN-99-021, Ref. 15)

This matrix is set to all zeros for all balance computations.

NF_CI_B3

Interaction corrected normal force (positive forward), lb

AF_CI_B3

Interaction corrected axial force (positive starboard), lb

SF_CI_B3

Interaction corrected side force (positive down), lb

PM_CI_B3

Interaction corrected pitching moment (positive nose right), ft-lb

RM_CI_B3

Interaction corrected rolling moment (positive nose down), ft-lb

YM_CI_B3

Interaction corrected yaw moment (positive clockwise looking towards balance), ft-lb

FCTH_CI_B3

Interaction corrected flex-coupling thrust (positive forward), lb

FCTQ_CI_B3

Interaction corrected flex-coupling torque,
(positive clockwise looking towards balance), ft-lb

Corrected Loads for Bias/Dbias (Balance Axis), Primary Gauge Set (B3)

The interaction corrected loads are then further corrected to account for bias/dbias. Note the suffix “_B3” for Primary balance gauge set. For the NFAC DAS balance load calculations, only linear terms will be used, so the Bias/Dbias corrections should all be zero, which would result in no change to the corrected loads. However, non-linear balance load calculation terms may be used in post-processing, so it is important that Bias/Dbias points are recorded for potential later use.

NF_CB_B3

Bias/dbias corrected normal force (positive forward), lb

AF_CB_B3

Bias/dbias corrected axial force (positive starboard, airplane mode), lb

SF_CB_B3

Bias/dbias corrected side force (positive down), lb

PM_CB_B3

Bias/dbias corrected pitching moment (positive nose right), ft-lb

RM_CB_B3

Bias/dbias corrected rolling moment (positive nose down), ft-lb

YM_CB_B3

Bias/dbias corrected yaw moment (positive clockwise looking towards balance), ft-lb

FCTH_CB_B3

Bias/dbias corrected flex-coupling thrust (positive forward), lb

FCTQ_CB_B3

Bias/dbias corrected flex-coupling torque,
(positive clockwise looking towards balance), ft-lb

Combined Balance Forces and Moments (Balance Axis), Primary Gauge Set (B3)

This section combines the bias-corrected balance and flex coupling loads into combined balance forces and moments.

NF_UNC_B3

Combined normal force (positive forward), lb
= NF_CB_B3 + FCTH_CB_B3

AF_UNC_B3

Combined axial force (positive starboard, airplane mode), lb
= AF_CB_B3

SF_UNC_B3

Combined side force (positive down), lb
= SF_CB_B3

PM_UNC_B3

Combined pitching moment (positive nose right), ft-lb
 = PM_CB_B3

RM_UNC_B3

Combined rolling moment (positive nose down), ft-lb
 = RM_CB_B3

YM_UNC_B3

Combined flex-coupling torque (positive clockwise looking towards balance), ft-lb. Note that residual torque from the balance corrects for bearing drag.
 = YM_CB_B3 + FCTQ_CB_B3

Equivalent Parameters

For the TTR/699 entry certain corrections were zero and some transformations were unity, with the result that several parameters are numerically identical:

$$FCTH_V_B3 = FCTH_B1$$

$$FCTQ_V_B3 = FCTQ_B1$$

$$NF_CI_B3 = NF_EU_B3 = NF_CB_B3$$

$$AF_CI_B3 = AF_EU_B3 = AF_CB_B3 = AF_UNC_B3$$

$$SF_CI_B3 = SF_EU_B3 = SF_CB_B3 = SF_UNC_B3$$

$$PM_CI_B3 = PM_EU_B3 = PM_CB_B3 = PM_UNC_B3$$

$$RM_CI_B3 = RM_EU_B3 = RM_CB_B3 = RM_UNC_B3$$

$$YM_CI_B3 = YM_EU_B3 = YM_CB_B3$$

$$FCTH_CI_B3 = FCTH_EU_B3 = FCTH_CB_B3$$

$$FCTQ_CI_B3 = FCTQ_EU_B3 = FCTQ_CB_B3$$

Balance Interactions Due to Applied Torque, Primary Gauge Set (B3)

This section provides the balance interaction values for axial force, side force, pitching moment and rolling moment due to the application of torque, FCTQ_EU_B3.

AF_TQI_B3

Torque interaction for axial force (positive starboard), lb
 = 0.024292 * FCTQ_EU_B3 - 3.2989e-07 * FCTQ_EU_B3**2

SF_TQI_B3

Torque interaction for side force (positive down), lb
 = 0.023019 * FCTQ_EU_B3 - 5.5312e-07 * FCTQ_EU_B3**2

PM_TQI_B3

Torque interaction for pitching moment (positive nose right), ft-lb
 = -0.080996 * FCTQ_EU_B3

RM_TQI_B3

Torque interaction for rolling moment (positive nose down), ft-lb
 $= -0.12352 * FCTQ_EU_B3 + 3.0981e-06 * FCTQ_EU_B3**2$

Rotor Balance Loads Corrected for Torque Interactions, Primary Gauge Set (B3)

This section corrects the xx_UNC loads for the effects of torque interactions.

NF_CTI_B3

Torque interaction corrected normal force (positive forward), lb
 $= NF_UNC_B3$

AF_CTI_B3

Torque interaction corrected normal force (positive forward), lb
 $= AF_UNC_B3 - AF_TQI_B3$

SF_CTI_B3

Torque interaction corrected axial force (positive starboard), lb
 $= SF_UNC_B3 - SF_TQI_B3$

PM_CTI_B3

Torque interaction corrected pitching moment (positive nose right), ft-lb
 $= PM_UNC_B3 - PM_TQI_B3$

RM_CTI_B3

Torque interaction corrected rolling moment (positive nose down), ft-lb
 $= RM_UNC_B3 - RM_TQI_B3$

YM_CTI_B3

Torque interaction corrected flex-coupling torque,
 (positive clockwise looking towards balance), ft-lb
 $= YM_UNC_B3$

Rotor Balance Loads Corrected for Weight Tares, Primary Gauge Set (B3)

This section corrects the xx_CTI loads for the effects of weight tares. Only the RM correction is non-zero, and there are no significant differences between balances. The complete equations are given below to show the process.

NF_CWT_B3

Weight tare corrected normal force (positive forward), lb
 $= NF_CTI_B3 - NFWTNRB_B3$

AF_CWT_B3

Weight tare corrected axial force (positive starboard), lb
 $= AF_CTI_B3 - AFWTNRB_B3$

SF_CWT_B3

Weight tare corrected side force (positive down), lb
 $= SF_CTI_B3 - SFWTNRB_B3$

PM_CWT_B3

Weight tare corrected pitching moment (positive nose right), ft-lb

$$= \text{PM_CTI_B3} - \text{PMWTNRB_B3}$$

RM_CWT_B3

Weight tare corrected rolling moment (positive nose down), ft-lb

$$= \text{RM_CTI_B3} - \text{RMWTNRB_B3}$$

YM_CWT_B3

Weight tare corrected flex-coupling torque,
(positive clockwise looking towards balance), ft-lb

$$= \text{YM_CTI_B3} - \text{TQWTNRB_B3}$$

Rotor Balance Loads Corrected for Aero Tares, Primary Gauge Set (B3)

This section corrects the xx_CWT loads for the effects of aerodynamic tares (determined with the rotor-off weight tare removed). If VKTS < 5 kts (hover data), then the aerodynamic tares are assumed to be zero. See Section D for aerodynamic tare equations.

NF_BAL_B3

Weight and aero tare corrected normal force (positive forward), lb

$$= \text{NF_CWT_B3} - \text{NFATR}$$

AF_BAL_B3

Weight and aero tare corrected axial force (positive starboard), lb

$$= \text{AF_CWT_B3} - \text{AFATR}$$

SF_BAL_B3

Weight and aero tare corrected side force (positive down), lb

$$= \text{SF_CWT_B3} - \text{SFATR}$$

PM_BAL_B3

Weight and aero tare corrected pitching moment (positive nose right), ft-lb

$$= \text{PM_CWT_B3} - \text{PMATR}$$

RM_BAL_B3

Weight and aero tare corrected rolling moment (positive starboard down), ft-lb

$$= \text{RM_CWT_B3} - \text{RMATR}$$

YM_BAL_B3

Weight and aero tare corrected flex-coupling torque,
(positive clockwise looking towards balance), ft-lb

$$= \text{YM_CWT_B3} - \text{TQATR}$$

Rotor Hub Loads in Body Axis, Primary Gauge Set (B3)

The body loads are obtained by transferring them from the balance center to the rotor hub and transformed from the balance axis to the shaft axis (Fig. 1). Since the shaft torque is the same in both balance axis and shaft axis, no coordinate transformation is necessary.

T_B3

Moment translating matrix, balance to body axis system (Eqns. 32&34, WN-99-021, Ref. 15). This matrix is the same for all balance computations.

$$= \begin{bmatrix} 0 & Z_REF & -Y_REF \\ -Z_REF & 0 & X_REF \\ Y_REF & -X_REF & 0 \end{bmatrix}$$

NF_BD_B3

Normal force at rotor hub in shaft axis (positive forward), lb

AF_BD_B3

Axial force at rotor hub in shaft axis (positive starboard), lb

SF_BD_B3

Side force at rotor hub in shaft axis (positive down), lb

PM_BD_B3

Pitching moment at rotor hub in shaft axis (positive nose right), ft-lb

RM_BD_B3

Rolling moment at rotor hub in shaft axis (positive nose down), ft-lb

YM_BD_B3

Yawing moment at rotor hub in shaft axis,
(positive clockwise looking towards balance), ft-lb

Rotor Hub Loads in Wind Axis, Primary Gauge Set (B3)

The aero tare corrected rotor hub forces and moments are then combined to form the rotor hub loads in the wind axis system. Equations are given in Ref. 14.

Note: TTR has a horizontal rotor shaft and therefore uses a non-traditional axis convention for Wind Axis loads; see Table 3 ff. Positive directions are defined facing upstream.

LIFT_W_B3

Lift force at rotor hub in wind axis (positive to right), lb

DRAG_W_B3

Drag force at rotor hub in wind axis (positive downstream), lb

SIDE_W_B3

Side force at rotor hub in wind axis (positive down), lb

PITCH_W_B3

Pitch moment at rotor hub in wind axis (positive CW looking down), ft-lb

ROLL_W_B3

Roll moment at rotor hub in wind axis (positive starboard down), ft-lb

YAW_W_B3

Yaw moment at rotor hub in wind axis (positive nose down), ft-lb

Wall-Effect Corrected Rotor Hub Loads in Wind Axis, Primary Gauge Set (B3)

The wall-effect corrected rotor hub loads in the wind axis system are calculated from

DALPHA_B3. This parameter is to be calculated using the Prandtl-Glauert wind tunnel wall correction method. Note that since the rotor axis is horizontal, angle of attack variations are accomplished by yawing the tunnel T-frame. Glauert corrections for airplane mode (propulsive efficiency) are in the section “Other Parameters, Primary Gauge Set”.

For the TTR, the slipstream is deflected sideways by rotor thrust, not vertically. The rotor balance axis system is rotated, so conventional equations can be used (here from the LRTA, Ref. 12) with the understanding that all corrections are in the rotated system.

DALPHA_B3

Correction offset for angle of attack, deg
 $= 57.3 * CAT * LIFT_W_B3 / (Q * CROSS_SECTION_AREA)$

CALPHA_B3

Corrected angle of attack, deg
 $= ALPHA + DALPHA_B3$
 Note: used as a trim condition for post-test analysis.

LIFT_WE_B3

Wall-effect corrected lift force at rotor hub in wind axis (positive to right), lb
 $= LIFT_W_B3 * COS(DALPHA1) - DRAG_W_B3 * SIN(DALPHA1)$

DRAG_WE_B3

Wall-effect corrected drag force at rotor hub in wind axis (positive downstream), lb
 $= DRAG_W_B3 * COS(DALPHA1) + LIFT_W_B3 * SIN(DALPHA1)$

SIDE_WE_B3

Wall-effect corrected side force at rotor hub in wind axis (positive down), lb
 $= SIDE_W_B3$

PITCH_WE_B3

Wall-effect corrected pitch moment at rotor hub in wind axis (positive CW looking down), ft-lb
 $= PITCH_W_B3$

ROLL_WE_B3

Wall-effect corrected roll moment at rotor hub in wind axis (positive starboard down), ft-lb
 $= ROLL_W_B3 * COS(DALPHA_B3) + YAW_W_B3 * SIN(DALPHA_B3)$

YAW_WE_B3

Wall-effect corrected yaw moment at rotor hub in wind axis (positive nose down), ft-lb
 $= YAW_W_B3 * COS(DALPHA_B3) - ROLL_W_B3 * SIN(DALPHA_B3)$

Rotor Coefficient Calculations (B3)

Rotor Coefficients in Body (Shaft) Axis, Primary Gauge Set (B3)

CNR_BD_B3

Rotor lift force coefficient in body axis (positive up)
= $NF_BD_B3 / CONSTF$

CAR_BD_B3

Rotor drag force coefficient in body axis (positive downstream)
= $AF_BD_B3 / CONSTF$

CYR_BD_B3

Rotor side force coefficient in body axis (positive starboard)
= $SF_BD_B3 / CONSTF$

CMYR_BD_B3

Rotor pitching moment coefficient in body axis (positive nose up)
= $PM_BD_B3 / CONSTM$

CMXR_BD_B3

Rotor rolling moment coefficient in body axis (positive starboard down)
= $RM_BD_B3 / CONSTM$

CMZR_BD_B3

Rotor yawing moment coefficient in body axis (positive starboard downstream)
= $YM_BD_B3 / CONSTM$

Rotor Coefficients in Wind Axis, Primary Gauge Set (B3)

CLR_W_B3

Rotor lift force coefficient in wind axis (positive to right)
= $LIFT_W_B3 / CONSTF$

CDR_W_B3

Rotor drag force coefficient in wind axis (positive downstream)
= $DRAG_W_B3 / CONSTF$

CYR_W_B3

Rotor side force coefficient in wind axis (positive down)
= $SIDE_W_B3 / CONSTF$

CMYR_W_B3

Rotor pitching moment coefficient in wind axis (positive CW looking down)
= $PITCH_W_B3 / CONSTM$

CMXR_W_B3

Rotor rolling moment coefficient in wind axis (positive starboard down)
= $ROLL_W_B3 / CONSTM$

CMZR_W_B3

Rotor yawing moment coefficient in wind axis (positive nose down)
= $YAW_W_B3 / CONSTM$

Rotor Coefficients in Corrected Wind Axis, Primary Gauge Set (B3)

CLR_WE_B3

Rotor lift force coefficient in corrected wind axis (positive to right)
= $LIFT_WE_B3 / CONSTF$

CDR_WE_B3

Rotor drag force coefficient in corrected wind axis (positive downstream)
= $DRAG_WE_B3 / CONSTF$

CYR_WE_B3

Rotor side force coefficient in corrected wind axis (positive down)
= $SIDE_WE_B3 / CONSTF$

CMYR_WE_B3

Rotor pitching moment coefficient in corrected wind axis (positive CW looking down)
= $PITCH_WE_B3 / CONSTM$

CMXR_WE_B3

Rotor rolling moment coefficient in corrected wind axis (positive starboard down)
= $ROLL_WE_B3 / CONSTM$

CMZR_WE_B3

Rotor yawing moment coefficient in corrected wind axis (positive nose down)
= $YAW_WE_B3 / CONSTM$

Rotor Coefficients Over Solidity in Body Axis, Primary Gauge Set (B3)

CNROS_BD_B3

Rotor lift force coefficient over solidity in body axis (positive up)
= $CNR_BD_B3 / SIGMA$

CAROS_BD_B3

Rotor drag force coefficient over solidity in body axis (positive downstream)
= $CAR_BD_B3 / SIGMA$

CYROS_BD_B3

Rotor side force coefficient over solidity in body axis (positive starboard)
= $CYR_BD_B3 / SIGMA$

CMYROS_BD_B3

Rotor pitching moment coefficient over solidity in body axis (positive nose up)
= $CMYR_BD_B3 / SIGMA$

CMXROS_BD_B3

Rotor rolling moment coefficient over solidity in body axis (positive starboard down)
= $CMXR_BD_B3 / SIGMA$

CMZROS_BD_B3

Rotor yawing moment coefficient over solidity in body axis (positive starboard downstream)

$$= \text{CMZR_BD_B3} / \text{SIGMA}$$

Rotor Coefficients Over Solidity in Wind Axis, Primary Gauge Set (B3)**CLROS_W_B3**

Rotor lift force coefficient over solidity in wind axis (positive to right)

$$= \text{CLR_W_B3} / \text{SIGMA}$$

CDROS_W_B3

Rotor drag force coefficient over solidity in wind axis (positive downstream)

$$= \text{CDR_W_B3} / \text{SIGMA}$$

CYROS_W_B3

Rotor side force coefficient over solidity in wind axis (positive down)

$$= \text{CYR_W_B3} / \text{SIGMA}$$

CMYROS_W_B3

Rotor pitching moment coefficient over solidity in wind axis (positive CW looking down)

$$= \text{CMYR_W_B3} / \text{SIGMA}$$

CMXRROS_W_B3

Rotor rolling moment coefficient over solidity in wind axis (positive starboard down)

$$= \text{CMXR_W_B3} / \text{SIGMA}$$

CMZROS_W_B3

Rotor yawing moment coefficient over solidity in wind axis (positive nose down)

$$= \text{CMZR_W_B3} / \text{SIGMA}$$

Rotor Coefficients Over Solidity in Corrected Wind Axis, Primary Gauge Set (B3)**CLROS_WE_B3**

Rotor lift force coefficient over solidity in corrected wind axis (positive to right)

$$= \text{CLR_WE_B3} / \text{SIGMA}$$

CDROS_WE_B3

Rotor drag force coefficient over solidity in corrected wind axis (positive downstream)

$$= \text{CDR_WE_B3} / \text{SIGMA}$$

CYROS_WE_B3

Rotor side force coefficient over solidity in corrected wind axis (positive down)

$$= \text{CYR_WE_B3} / \text{SIGMA}$$

CMYROS_WE_B3

Rotor pitching moment coefficient over solidity in corrected wind axis (positive CW looking down)

$$= \text{CMYR_WE_B3} / \text{SIGMA}$$

CMXROS_WE_B3

Rotor rolling moment coefficient over solidity in corrected wind axis (positive starboard down)

$$= \text{CMXR_WE_B3} / \text{SIGMA}$$

CMZROS_WE_B3

Rotor yawing moment coefficient over solidity in corrected wind axis (positive nose down)

$$= \text{CMZR_WE_B3} / \text{SIGMA}$$

Miscellaneous Parameters (B3)Standard Rotor Parameters, Primary Gauge Set (B3)

Note: TTR has a horizontal rotor shaft and therefore uses a non-traditional axis convention for rotor loads; see Table 1 ff. Positive directions are defined facing upstream.

THRUST_B3

Corrected rotor balance thrust in shaft axis (positive forward), lb

$$= \text{NF_BD_B3}$$

CT_B3

Rotor balance thrust coefficient

$$= \text{CNR_BD_B3}$$

CTOS_B3

Rotor balance thrust coefficient over solidity

$$= \text{CNROS_BD_B3}$$

HFORCE_B3

Corrected rotor balance H-force (positive to right), lb

$$= \text{AF_BD_B3}$$

CH_B3

Rotor balance H-force coefficient

$$= \text{CAR_BD_B3}$$

CHOS_B3

Rotor balance H-force coefficient over solidity

$$= \text{CAROS_BD_B3}$$

YFORCE_B3

Rotor balance Y-force (positive down)

$$= \text{SF_BD_B3}$$

X-Force Parameters, Primary Gauge Set (B3)**XFORCE_B3**

Corrected rotor balance X-force (positive downstream), lb

$$= - \text{DRAG_WE_B3}$$

CX_B3

Rotor balance X-force coefficient
 $= - \text{CDR_WE_B3}$

CXOS_B3

Rotor balance X-force coefficient over solidity
 $= - \text{CDROS_WE_B3}$

Rotor Torque and Power, Primary Gauge Set (B3)**TORQ_B3**

Torque from rotor balance, ft-lb
 $= \text{YM_BD_B3}$

PWR_B3

Power from rotor balance yaw moment, ft-lb/sec
 $= \text{TORQ_B3} * \text{OMR/ROTRAD}$

HP_B3

Horsepower from rotor balance, hp
 $= \text{PWR_B3} / 550$

CP_B3

Rotor power coefficient from rotor balance
 $= \text{PWR_B3} / \text{CONSTP}$

CPOS_B3

Rotor power (torque) coefficient over solidity from rotor balance
 $= \text{CP_B3} / \text{SIGMA}$

Ideal and Non-Ideal Power Coefficients, Primary Gauge Set (B3)**CPOS_ID_B3**

Ideal power coefficient over solidity
 IF (MU < SQRT (0.5 * CT_B3)) THEN
 $\text{CPOS_ID_B3} = \text{SQRT}(\text{SIGMA}/2.0) * (\text{CTOS_B3})^{(3.0/2.0)}$
 ELSE
 $\text{CPOS_ID_B3} = 0.5 * \text{SIGMA} * ((\text{CLROS_WE_B3})^{**2}) / \text{MU}$
 $+ \text{CXOS_B3} * \text{MU}$
 ENDIF

CPOS_NI_B3

Coefficient of non-ideal power over solidity
 $= \text{CPOS_B3} - \text{CPOS_ID_B3}$

CPRAT_B3

Ratio of measured power coefficient to the ideal power coefficient
 $= \text{CPOS_B3} / \text{CPOS_ID_B3}$

Other Parameters, Primary Gauge Set (B3)

DEQ_B3

Equivalent drag, lb
= DRAG_WE_B3 + PWR_B3 / VFPS

LOD_B3

Rotor lift-to-drag ratio
= LIFT_WE_B3 / DEQ_B3

FE_B3

Rotor equivalent drag area, ft²
IF(Q > 1.0) THEN
= DRAG_WE_B3 / Q
ELSE
= 0
ENDIF

ATANXOL_B3

Angle of resultant rotor force, deg
= ARCTAN(-DRAG_WE_B3 / LIFT_WE_B3) * RTD

FMERIT_B3

Hover figure of merit
= CPOS_ID_B3 / CPOS_B3

VOVH_B3

Non-dimensional hover induced velocity
= VFPS / SQRT(THRUST_B3 / (2 * RHO * PI * ROTRAD**2))

ETAP_B3

Propeller propulsive efficiency
= MUZ * CT_B3 / CP_B3

VPOV_B3

Glauert propeller correction factor (V'/V)
Applicable only for positive thrust in airplane mode or vertical climb, near 0 or 180 deg yaw. CT>0 and Q>0.01 prevent divide by zero.

IF (CT_B3 > 0 and ABS(ALPHA) > 85 deg and Q > 0.01) THEN
= 1 - (ALPHA1 * CT_B3 / MUZ**2) / (2 * SQRT(1 + 2 * CT_B3 / MUZ**2))
ELSE
= 1
ENDIF

Where ALPHA1 is the Glauert area ratio (defined in the Constants section).

ETAP_GC_B3

Propulsive efficiency with Glauert correction
= VPOV_B3 * ETAP_B3

MUZ_GC_B3

Axial advance ratio with Glauert correction
= MUZ * VPOV_B3

Mean Performance Parameters, Primary Gauge Set (B3)

Some of the performance parameters calculated in the previous sections could provide spurious results if instantaneous values of the input parameters are near zero (applicable when one or more of the parameters are in the denominator of the equation). These parameters should be recomputed using only the mean values of the individual inputs. Using LOD_B3 as an example, the new parameter would be

$$\text{LOD_B3_ME} = \text{mean}(\text{LIFT_WE_B3}) / \text{mean}(\text{DEQ_B3})$$

where the result is a single number for each data point (rather than a time history).

The following parameters should be calculated in this way:

ATANXOL_B3_ME
CPOS_ID_B3_ME
CPOS_NI_B3_ME
CPRAT_B3_ME
DEQ_B3_ME
FE_B3_ME
FMERIT_B3_ME
LOD_B3_ME
VOVH_B3_ME
ETAP_B3_ME
ETAP_GC_B3_ME
VPOV_B3_ME
MUZ_GC_B3_ME

For similar reasons, there are tests for divide by zero not explicitly defined in this document.

G Rotor Balance Data Reduction, Secondary Gauge Set (B4)

The suffix “_B4” is used to denote the traditional load calculations using the Secondary gauge set (Ref. 10). The process for the Secondary set is identical to that for the Primary set; the following section is almost identical to Section F.

Weight Tare Corrections (B4)

Weight Tares with Non-rotating Spinner (Rotor Off), Secondary Gauge Set (B4)

These weight tares are obtained with wind off, non-rotating spinner with cover plates installed, and hub and blades off. Data from specific runs are analyzed to obtain the curve fit/tare coefficients. These data are curve-fit as functions of shaft angle (T-frame angle). The curve fits were determined after installation into the test section.

Note: These parameters are not normally stored, but are shown here to clarify the process.

NFWTNSP_B4

Weight tare with nonrotating spinner for balance normal force (positive forward), lb
= 0

AFWTNSP_B4

Weight tare with nonrotating spinner for balance axial force (positive starboard), lb
= 0

SFWTNSP_B4

Weight tare with nonrotating spinner for balance side force (positive down), lb
= 0

PMWTNSP_B4

Weight tare with nonrotating spinner for balance pitching moment (positive nose right), ft-lb
= 0

RMWTNSP_B4

Weight tare with nonrotating spinner for balance rolling moment (positive nose down), ft-lb
= RMWTNRB

Effectively = 0 with the rotor off and the swashplate in fixed position.

TQWTNSP_B4

Weight tare with nonrotating spinner for flex-coupling torque,
(positive clockwise looking towards balance), ft-lb
= 0

Weight Tares with Non-rotating Rotor (Spinner On), Secondary Gauge Set (B4)

These weight tares are obtained with wind off, non-rotating hub, and blades on. Data from specific runs are analyzed to obtain the curve fit/tare coefficients. These data are curve-fit as functions of shaft angle and swashplate position. The curve fits were determined after installation into the test section; only the RM variation with swashplate position is non-zero. There was no significant difference between balances, so the distinction is here dropped.

Note: These parameters are not normally stored, but are shown here to clarify the process.

NFWTNRB_B4

Weight tare with nonrotating blade for balance normal force (positive forward), lb
= 0

AFWTNRB_B4

Weight tare with nonrotating blade for balance axial force (positive starboard), lb
= 0

SFWTNRB_B4

Weight tare with nonrotating blade for balance side force (positive down), lb
= 0

PMWTNRB_B4

Weight tare with nonrotating blade for balance pitching moment (positive nose right),
ft-lb
= 0

RMWTNRB_B4

Weight tare with nonrotating blade for balance rolling moment (positive nose down),
ft-lb

$$\text{RMWTNRB_B4} = 18.0 * \text{SPCOLL}$$

Stored as RMWTNRB because there is no physical difference between _B3 and _B4.

TQWTNRB_B4

Weight tare with nonrotating blade for flex-coupling torque,
(positive clockwise looking towards balance), ft-lb
= 0

Balance Load Calculations (B4)

Uncorrected Load Gauge Readings (Balance Axis), Secondary Gauge Set (B4)

Combine RCAL corrected measurements into load gauge readings (V) in the balance axis system. Note the suffix “_B4” for Primary balance gauge set. These measurements are determined by multiplying the 14 individual primary balance and flex-coupling gauge voltages by the matrix [SL_B4]; the [SL_B4] matrix is the same as used in the LRTA data reduction (Ref. 12).

SL_B4

Balance gauge voltages to load gauge (calibration) voltages matrix (Eqns. 8-10, WN-99-021, Ref. 15). This matrix is the same for the B3 and B4 balance computations.

$$= \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

NF_V_B4

Load readings for normal force (positive forward), V

AF_V_B4

Load readings for axial force (positive starboard), V

SF_V_B4

Load readings for side force (positive down), V

PM_V_B4

Load readings for pitching moment (positive nose right), V

RM_V_B4

Load readings for rolling moment (positive nose down), V

YM_V_B4

Load readings for yaw moment (positive clockwise looking towards balance), V

FCTH_V_B4

Load readings for flex-coupling thrust (positive forward), V

FCTQ_V_B4

Load readings for flex-coupling torque,
(positive clockwise looking towards balance), V

Uncorrected Balance Loads (Balance Axis), Secondary Gauge Set (B4)

Convert combined load readings to uncorrected loads in engineering units (EU) expressed in the balance axis system. Note the suffix “_B4” for Secondary balance gauge set. These are determined by multiplying the eight uncorrected load gauge readings by the matrix [D1]; the [D1] matrix is unique for this set of gauges.

D1_B4

First order calibration matrix. (Eqn. 11, WN-99-021, Ref. 15)
This matrix is provided as a text file.

NF_EU_B4

Uncorrected normal force (positive forward), lb

AF_EU_B4

Uncorrected axial force (positive starboard), lb

SF_EU_B4

Uncorrected side force (positive down), lb

PM_EU_B4

Uncorrected pitching moment (positive nose right), ft-lb

RM_EU_B4

Uncorrected rolling moment (positive nose down), ft-lb

YM_EU_B4

Uncorrected yaw moment (positive clockwise looking towards balance), ft-lb

FCTH_EU_B4

Uncorrected flex-coupling thrust (positive forward), lb

FCTQ_EU_B4

Uncorrected flex-coupling torque (positive clockwise looking towards balance), ft-lb

Corrected Loads for Non-linear Interactions (Balance Axis), Secondary Gauge Set (B4)

Next, the load-gauge engineering unit data above (XX_EU_B4) are corrected for non-linear model terms for gauge interactions and cross-component loading. Note the suffix “_B4” for Secondary balance gauge set. These are determined by multiplying the eight uncorrected balance loads by the matrix [D2]. For the NFAC DAS balance load calculations, only linear terms will be used, so the [D2] matrix is all zeros, which means the corrected balance loads are the same as the uncorrected balance loads.

D2_B4

Second order calibration matrix. (Eqn. 12a, WN-99-021, Ref. 15)

This matrix is set to all zeros for all balance computations.

NF_CI_B4

Interaction corrected normal force (positive forward), lb

AF_CI_B4

Interaction corrected axial force (positive starboard), lb

SF_CI_B4

Interaction corrected side force (positive down), lb

PM_CI_B4

Interaction corrected pitching moment (positive nose right), ft-lb

RM_CI_B4

Interaction corrected rolling moment (positive nose down), ft-lb

YM_CI_B4

Interaction corrected yaw moment (positive clockwise looking towards balance), ft-lb

FCTH_CI_B4

Interaction corrected flex-coupling thrust (positive forward), lb

FCTQ_CI_B4

Interaction corrected flex-coupling torque,
(positive clockwise looking towards balance), ft-lb

Corrected Loads for Bias/Dbias (Balance Axis), Secondary Gauge Set (B4)

The interaction corrected loads are then further corrected to account for bias/dbias. Note the suffix “_B4” for Secondary balance gauge set. For the NFAC DAS balance load calculations, only linear terms will be used, so the Bias/Dbias corrections should all be zero, which would result in no change to the corrected loads. However, non-linear balance load calculation terms may be used in post-processing, so it is important that Bias/Dbias points are recorded for potential later use.

NF_CB_B4

Bias/dbias corrected normal force (positive forward), lb

AF_CB_B4

Bias/dbias corrected axial force (positive starboard, airplane mode), lb

SF_CB_B4

Bias/dbias corrected side force (positive down), lb

PM_CB_B4

Bias/dbias corrected pitching moment (positive nose right), ft-lb

RM_CB_B4

Bias/dbias corrected rolling moment (positive nose down), ft-lb

YM_CB_B4

Bias/dbias corrected yaw moment (positive clockwise looking towards balance), ft-lb

FCTH_CB_B4

Bias/dbias corrected flex-coupling thrust (positive forward), lb

FCTQ_CB_B4

Bias/dbias corrected flex-coupling torque,
(positive clockwise looking towards balance), ft-lb

Combined Balance Forces and Moments (Balance Axis), Secondary Gauge Set (B4)

This section combines the bias-corrected balance and flex coupling loads into combined balance forces and moments.

NF_UNC_B4

Combined normal force (positive forward), lb
= NF_CB_B4 + FCTH_CB_B4

AF_UNC_B4

Combined axial force (positive starboard, airplane mode), lb
= AF_CB_B4

SF_UNC_B4

Combined side force (positive down), lb
= SF_CB_B4

PM_UNC_B4

Combined pitching moment (positive nose right), ft-lb
 = PM_CB_B4

RM_UNC_B4

Combined rolling moment (positive nose down), ft-lb
 = RM_CB_B4

YM_UNC_B4

Combined flex-coupling torque (positive clockwise looking towards balance), ft-lb. Note that residual torque from the balance corrects for bearing drag.
 = YM_CB_B4 + FCTQ_CB_B4

Equivalent parameters

For the TTR/699 entry certain corrections were zero and some transformations were unity, with the result that several parameters are numerically identical:

$$FCTH_V_B4 = FCTH_B2$$

$$FCTQ_V_B4 = FCTQ_B2$$

$$NF_CI_B4 = NF_EU_B4 = NF_CB_B4$$

$$AF_CI_B4 = AF_EU_B4 = AF_CB_B4 = AF_UNC_B4$$

$$SF_CI_B4 = SF_EU_B4 = SF_CB_B4 = SF_UNC_B4$$

$$PM_CI_B4 = PM_EU_B4 = PM_CB_B4 = PM_UNC_B4$$

$$RM_CI_B4 = RM_EU_B4 = RM_CB_B4 = RM_UNC_B4$$

$$YM_CI_B4 = YM_EU_B4 = YM_CB_B4$$

$$FCTH_CI_B4 = FCTH_EU_B4 = FCTH_CB_B4$$

$$FCTQ_CI_B4 = FCTQ_EU_B4 = FCTQ_CB_B4$$

Balance Interactions Due to Applied Torque, Primary Gauge Set (B4)

This section provides the balance interaction values for axial force, side force, pitching moment and rolling moment due to the application of torque, FCTQ_EU_B4.

AF_TQI_B4

Torque interaction for axial force (positive starboard), lb
 = $0.023007 * FCTQ_EU_B4 - 2.9111e-07 * FCTQ_EU_B4^{**2}$

SF_TQI_B4

Torque interaction for side force (positive down), lb
 = $0.025073 * FCTQ_EU_B4 - 6.3078e-07 * FCTQ_EU_B4^{**2}$

PM_TQI_B4

Torque interaction for pitching moment (positive nose right), ft-lb
 = $-0.084463 * FCTQ_EU_B4$

RM_TQI_B4

Torque interaction for rolling moment (positive nose down), ft-lb
 $= -0.14038 * FCTQ_EU_B4 + 3.7003e-06 * FCTQ_EU_B4^{**2}$

Rotor Balance Loads Corrected for Torque Interactions, Primary Gauge Set (B4)

This section corrects the xx_UNC loads for the effects of torque interactions.

NF_CTI_B4

Torque interaction corrected normal force (positive forward), lb
 $= NF_UNC_B4$

AF_CTI_B4

Torque interaction corrected normal force (positive forward), lb
 $= AF_UNC_B4 - AF_TQI_B4$

SF_CTI_B4

Torque interaction corrected axial force (positive starboard), lb
 $= SF_UNC_B4 - SF_TQI_B4$

PM_CTI_B4

Torque interaction corrected pitching moment (positive nose right), ft-lb
 $= PM_UNC_B4 - PM_TQI_B4$

RM_CTI_B4

Torque interaction corrected rolling moment (positive nose down), ft-lb
 $= RM_UNC_B4 - RM_TQI_B4$

YM_CTI_B4

Torque interaction corrected flex-coupling torque,
 (positive clockwise looking towards balance), ft-lb
 $= YM_UNC_B4$

Rotor Balance Loads Corrected for Weight Tares, Secondary Gauge Set (B4)

This section corrects the xx_CTI loads for the effects of weight tares. Only the RM correction is non-zero, and there are no significant differences between balances. The complete equations are given below to show the process.

NF_CWT_B4

Weight tare corrected normal force (positive forward), lb
 $= NF_CTI_B4 - NFWTNRB_B4$

AF_CWT_B4

Weight tare corrected axial force (positive starboard), lb
 $= AF_CTI_B4 - AFWTNRB_B4$

SF_CWT_B4

Weight tare corrected side force (positive down), lb
 $= SF_CTI_B4 - SFWTNRB_B4$

PM_CWT_B4

Weight tare corrected pitching moment (positive nose right), ft-lb

$$= \text{PM_CTI_B4} - \text{PMWTNRB_B4}$$

RM_CWT_B4

Weight tare corrected rolling moment (positive nose down), ft-lb

$$= \text{RM_CTI_B4} - \text{RMWTNRB_B4}$$

YM_CWT_B4

Weight tare corrected flex-coupling torque,
(positive clockwise looking towards balance), ft-lb

$$= \text{YM_CTI_B4} - \text{TQWTNRB_B4}$$

Rotor Balance Loads Corrected for Aero Tares, Secondary Gauge Set (B4)

This section corrects the xx_CWT loads for the effects of aerodynamic tares (determined with the rotor-off weight tare removed). If VKTS < 5 kts (hover data), then the aerodynamic tares are assumed to be zero. See Section D for aerodynamic tare equations.

NF_BAL_B4

Weight and aero tare corrected normal force (positive forward), lb

$$= \text{NF_CWT_B4} - \text{NFATR}$$

AF_BAL_B4

Weight and aero tare corrected axial force (positive starboard), lb

$$= \text{AF_CWT_B4} - \text{AFATR}$$

SF_BAL_B4

Weight and aero tare corrected side force (positive down), lb

$$= \text{SF_CWT_B4} - \text{SFATR}$$

PM_BAL_B4

Weight and aero tare corrected pitching moment (positive nose right), ft-lb

$$= \text{PM_CWT_B4} - \text{PMATR}$$

RM_BAL_B4

Weight and aero tare corrected rolling moment (positive starboard down), ft-lb

$$= \text{RM_CWT_B4} - \text{RMATR}$$

YM_BAL_B4

Weight and aero tare corrected flex-coupling torque,
(positive clockwise looking towards balance), ft-lb

$$= \text{YM_CWT_B4} - \text{TQATR}$$

Rotor Hub Loads in Body Axis, Secondary Gauge Set (B4)

The body loads are obtained by transferring them from the balance center to the rotor hub and transformed from the balance axis to the shaft axis (Fig. 1). Since the shaft torque is the same in both balance axis and shaft axis, no coordinate transformation is necessary.

T_B4

Moment translating matrix, balance to body axis system. (Eqns. 32-34, WN-99-021, Ref. 15). This matrix is the same for all balance computations.

$$= \begin{bmatrix} 0 & Z_{REF} & -Y_{REF} \\ -Z_{REF} & 0 & X_{REF} \\ Y_{REF} & -X_{REF} & 0 \end{bmatrix}$$

NF_BD_B4

Normal force at rotor hub in shaft axis (positive forward), lb

AF_BD_B4

Axial force at rotor hub in shaft axis (positive starboard), lb

SF_BD_B4

Side force at rotor hub in shaft axis (positive down), lb

PM_BD_B4

Pitching moment at rotor hub in shaft axis (positive nose right), ft-lb

RM_BD_B4

Rolling moment at rotor hub in shaft axis (positive nose down), ft-lb

YM_BD_B4

Yawing moment at rotor hub in shaft axis,
(positive clockwise looking towards balance), ft-lb

Rotor Hub Loads in Wind Axis, Secondary Gauge Set (B4)

The aero tare corrected rotor hub forces and moments are then combined to form the rotor hub loads in the wind axis system. Equations are given in Ref. 14.

Note: TTR has a horizontal rotor shaft and therefore uses a non-traditional axis convention for Wind Axis loads; see Table 1 ff. Positive directions are defined facing upstream.

LIFT_W_B4

Lift force at rotor hub in wind axis (positive to right), lb

DRAG_W_B4

Drag force at rotor hub in wind axis (positive downstream), lb

SIDE_W_B4

Side force at rotor hub in wind axis (positive down), lb

PITCH_W_B4

Pitch moment at rotor hub in wind axis (positive CW looking down), ft-lb

ROLL_W_B4

Roll moment at rotor hub in wind axis (positive starboard down), ft-lb

YAW_W_B4

Yaw moment at rotor hub in wind axis (positive nose down), ft-lb

Wall-Effect Corrected Rotor Hub Loads in Wind Axis, Secondary Gauge Set (B4)

The wall-effect corrected rotor hub loads in the wind axis system are calculated from DALPHA_B4. This parameter is to be calculated using the Prandtl-Glauert wind tunnel wall

correction method. Note that since the rotor axis is horizontal, angle of attack variations are accomplished by yawing the tunnel T-frame. Glauert corrections for airplane mode (propulsive efficiency) are in the section “Other Parameters, Secondary Gauge Set”.

For the TTR, the slipstream is deflected sideways by rotor thrust, not vertically. The rotor balance axis system is rotated, so conventional equations can be used (here from the LRTA, Ref. 12) with the understanding that all corrections are in the rotated system.

DALPHA_B4

Correction offset for angle of attack, deg
 $= 57.3 * CAT * LIFT_W_B4 / (Q * CROSS_SECTION_AREA)$

CALPHA_B4

Corrected angle of attack, deg
 $= ALPHA + DALPHA_B4$
 Used as a trim condition for post-test analysis.

LIFT_WE_B4

Wall-effect corrected lift force at rotor hub in wind axis (positive to right), lb
 $= LIFT_W_B4 * COS(DALPHA1) - DRAG_W_B4 * SIN(DALPHA1)$

DRAG_WE_B4

Wall-effect corrected drag force at rotor hub in wind axis (positive downstream), lb
 $= DRAG_W_B4 * COS(DALPHA1) + LIFT_W_B4 * SIN(DALPHA1)$

SIDE_WE_B4

Wall-effect corrected side force at rotor hub in wind axis (positive down), lb
 $= SIDE_W_B4$

PITCH_WE_B4

Wall-effect corrected pitch moment at rotor hub in wind axis (positive CW looking down), ft-lb
 $= PITCH_W_B4$

ROLL_WE_B4

Wall-effect corrected roll moment at rotor hub in wind axis (positive starboard down), ft-lb
 $= ROLL_W_B4 * COS(DALPHA_B4) + YAW_W_B4 * SIN(DALPHA_B4)$

YAW_WE_B4

Wall-effect corrected yaw moment at rotor hub in wind axis (positive nose down), ft-lb
 $= YAW_W_B4 * COS(DALPHA_B4) - ROLL_W_B4 * SIN(DALPHA_B4)$

Rotor Coefficient Calculations (B4)

Rotor Coefficients in Body (Shaft) Axis, Secondary Gauge Set (B4)

CNR_BD_B4

Rotor lift force coefficient in body axis (positive up)
 $= NF_BD_B4 / CONSTF$

CAR_BD_B4

Rotor drag force coefficient in body axis (positive downstream)
 $= AF_BD_B4 / CONSTF$

CYR_BD_B4

Rotor side force coefficient in body axis (positive starboard)
 $= SF_BD_B4 / CONSTF$

CMYR_BD_B4

Rotor pitching moment coefficient in body axis (positive nose up)
 $= PM_BD_B4 / CONSTM$

CMXR_BD_B4

Rotor rolling moment coefficient in body axis (positive starboard down)
 $= RM_BD_B4 / CONSTM$

CMZR_BD_B4

Rotor yawing moment coefficient in body axis (positive starboard downstream)
 $= YM_BD_B4 / CONSTM$

Rotor Coefficients in Wind Axis, Secondary Gauge Set (B4)**CLR_W_B4**

Rotor lift force coefficient in wind axis (positive to right)
 $= LIFT_W_B4 / CONSTF$

CDR_W_B4

Rotor drag force coefficient in wind axis (positive downstream)
 $= DRAG_W_B4 / CONSTF$

CYR_W_B4

Rotor side force coefficient in wind axis (positive down)
 $= SIDE_W_B4 / CONSTF$

CMYR_W_B4

Rotor pitching moment coefficient in wind axis (positive CW looking down)
 $= PITCH_W_B4 / CONSTM$

CMXR_W_B4

Rotor rolling moment coefficient in wind axis (positive starboard down)
 $= ROLL_W_B4 / CONSTM$

CMZR_W_B4

Rotor yawing moment coefficient in wind axis (positive nose down)
 $= YAW_W_B4 / CONSTM$

Rotor Coefficients in Corrected Wind Axis, Secondary Gauge Set (B4)**CLR_WE_B4**

Rotor lift force coefficient in corrected wind axis (positive to right)
 $= LIFT_WE_B4 / CONSTF$

CDR_WE_B4

Rotor drag force coefficient in corrected wind axis (positive downstream)
= DRAG_WE_B4 / CONSTF

CYR_WE_B4

Rotor side force coefficient in corrected wind axis (positive down)
= SIDE_WE_B4 / CONSTF

CMYR_WE_B4

Rotor pitching moment coefficient in corrected wind axis (positive CW looking down)
= PITCH_WE_B4 / CONSTM

CMXR_WE_B4

Rotor rolling moment coefficient in corrected wind axis (positive starboard down)
= ROLL_WE_B4 / CONSTM

CMZR_WE_B4

Rotor yawing moment coefficient in corrected wind axis (positive nose down)
= YAW_WE_B4 / CONSTM

Rotor Coefficients Over Solidity in Body Axis, Secondary Gauge Set (B4)**CNROS_BD_B4**

Rotor lift force coefficient over solidity in body axis (positive up)
= CNR_BD_B4 / SIGMA

CAROS_BD_B4

Rotor drag force coefficient over solidity in body axis (positive downstream)
= CAR_BD_B4 / SIGMA

CYROS_BD_B4

Rotor side force coefficient over solidity in body axis (positive starboard)
= CYR_BD_B4 / SIGMA

CMYROS_BD_B4

Rotor pitching moment coefficient over solidity in body axis (positive nose up)
= CMYR_BD_B4 / SIGMA

CMXROS_BD_B4

Rotor rolling moment coefficient over solidity in body axis (positive starboard down)
= CMXR_BD_B4 / SIGMA

CMZROS_BD_B4

Rotor yawing moment coefficient over solidity in body axis (positive starboard downstream)

$$= \text{CMZR_BD_B4} / \text{SIGMA}$$

Rotor Coefficients Over Solidity in Wind Axis, Secondary Gauge Set (B4)**CLROS_W_B4**

Rotor lift force coefficient over solidity in wind axis (positive to right)

$$= \text{CLR_W_B4} / \text{SIGMA}$$

CDROS_W_B4

Rotor drag force coefficient over solidity in wind axis (positive downstream)

$$= \text{CDR_W_B4} / \text{SIGMA}$$

CYROS_W_B4

Rotor side force coefficient over solidity in wind axis (positive down)

$$= \text{CYR_W_B4} / \text{SIGMA}$$

CMYROS_W_B4

Rotor pitching moment coefficient over solidity in wind axis (positive CW looking down)

$$= \text{CMYR_W_B4} / \text{SIGMA}$$

CMXROS_W_B4

Rotor rolling moment coefficient over solidity in wind axis (positive starboard down)

$$= \text{CMXR_W_B4} / \text{SIGMA}$$

CMZROS_W_B4

Rotor yawing moment coefficient over solidity in wind axis (positive nose down)

$$= \text{CMZR_W_B4} / \text{SIGMA}$$

Rotor Coefficients Over Solidity in Corrected Wind Axis, Secondary Gauge Set (B4)**CLROS_WE_B4**

Rotor lift force coefficient over solidity in corrected wind axis (positive to right)

$$= \text{CLR_WE_B4} / \text{SIGMA}$$

CDROS_WE_B4

Rotor drag force coefficient over solidity in corrected wind axis (positive downstream)

$$= \text{CDR_WE_B4} / \text{SIGMA}$$

CYROS_WE_B4

Rotor side force coefficient over solidity in corrected wind axis (positive down)

$$= \text{CYR_WE_B4} / \text{SIGMA}$$

CMYROS_WE_B4

Rotor pitching moment coefficient over solidity in corrected wind axis (positive CW looking down)

$$= \text{CMYR_WE_B4} / \text{SIGMA}$$

CMXROS_WE_B4

Rotor rolling moment coefficient over solidity in corrected wind axis (positive starboard down)

$$= \text{CMXR_WE_B4} / \text{SIGMA}$$

CMZROS_WE_B4

Rotor yawing moment coefficient over solidity in corrected wind axis (positive nose down)

$$= \text{CMZR_WE_B4} / \text{SIGMA}$$

Miscellaneous Parameters (B4)Standard Rotor Parameters, Secondary Gauge Set (B4)

Note: TTR has a horizontal rotor shaft and therefore uses a non-traditional axis convention for rotor loads; see Table 1 ff. Positive directions are defined facing upstream.

THRUST_B4

Corrected rotor balance thrust in shaft axis (positive forward), lb

$$= \text{NF_BD_B4}$$

CT_B4

Rotor balance thrust coefficient

$$= \text{CNR_BD_B4}$$

CTOS_B4

Rotor balance thrust coefficient over solidity

$$= \text{CNROS_BD_B4}$$

HFORCE_B4

Corrected rotor balance H-force (positive to right), lb

$$= \text{AF_BD_B4}$$

CH_B4

Rotor balance H-force coefficient

$$= \text{CAR_BD_B4}$$

CHOS_B4

Rotor balance H-force coefficient over solidity

$$= \text{CAROS_BD_B4}$$

YFORCE_B4

Rotor balance Y-force (positive down)

$$= \text{SF_BD_B4}$$

X-Force Parameters, Secondary Gauge Set (B4)**XFORCE_B4**

Corrected rotor balance X-force (positive downstream), lb

$$= - \text{DRAG_WE_B4}$$

CX_B4

Rotor balance X-force coefficient
 $= - \text{CDR_WE_B4}$

CXOS_B4

Rotor balance X-force coefficient over solidity
 $= - \text{CDROS_WE_B4}$

Rotor Torque and Power, Secondary Gauge Set (B4)**TORQ_B4**

Torque from rotor balance, ft-lb
 $= \text{YM_BD_B4}$

PWR_B4

Power from rotor balance yaw moment, ft-lb/sec
 $= \text{TORQ_B4} * \text{OMR/ROTRAD}$

HP_B4

Horsepower from rotor balance, hp
 $= \text{PWR_B4} / 550$

CP_B4

Rotor power coefficient from rotor balance
 $= \text{PWR_B4} / \text{CONSTP}$

CPOS_B4

Rotor power (torque) coefficient over solidity from rotor balance
 $= \text{CP_B4} / \text{SIGMA}$

Ideal and Non-Ideal Power Coefficients, Secondary Gauge Set (B4)**CPOS_ID_B4**

Ideal power coefficient over solidity
 IF (MU < SQRT (0.5 * CT_B4)) THEN
 $\text{CPOS_ID_B4} = \text{SQRT}(\text{SIGMA} / 2.0) * (\text{CTOS_B4})^{(3.0 / 2.0)}$
 ELSE
 $\text{CPOS_ID_B4} = 0.5 * \text{SIGMA} * ((\text{CLROS_WE_B4})^{**2}) / \text{MU}$
 $+ \text{CXOS_B4} * \text{MU}$
 ENDIF

CPOS_NI_B4

Coefficient of non-ideal power over solidity
 $= \text{CPOS_B4} - \text{CPOS_ID_B4}$

CPRAT_B4

Ratio of measured power coefficient to the ideal power coefficient
 $= \text{CPOS_B4} / \text{CPOS_ID_B4}$

Other Parameters, Secondary Gauge Set (B4)

DEQ_B4

Equivalent drag, lb
= DRAG_WE_B4 + PWR_B4 / VFPS

LOD_B4

Rotor lift-to-drag ratio
= LIFT_WE_B4 / DEQ_B4

FE_B4

Rotor equivalent drag area, ft²
IF(Q > 1.0) THEN
= DRAG_WE_B4 / Q
ELSE
= 0
ENDIF

ATANXOL_B4

Angle of resultant rotor force, deg
= ARCTAN(-DRAG_WE_B4 / LIFT_WE_B4) * RTD

FMERIT_B4

Hover figure of merit
= CPOS_ID_B4 / CPOS_B4

VOVH_B4

Non-dimensional hover induced velocity
= VFPS/SQRT(THRUST_B4 / (2 * RHO * PI * ROTRAD**2))

ETAP_B4

Propeller propulsive efficiency
= MUZ * CT_B4 / CP_B4

VPOV_B4

Glauert propeller correction factor (V'/V)
Applicable only for positive thrust in airplane mode or vertical climb, near 0 or 180 deg yaw. CT>0 and Q>0.01 prevent divide by zero.

IF (CT_B4 > 0 and ABS(ALPHA) > 85 deg and Q > 0.01) THEN
= 1 - (ALPHA1 * CT_B4 / MUZ**2) / (2 * SQRT(1 + 2 * CT_B4 / MUZ**2))
ELSE
= 1
ENDIF

Where ALPHA1 is the Glauert area ratio (defined in the Constants section).

ETAP_GC_B4

Propulsive efficiency with Glauert correction
= VPOV_B4 * ETAP_B4

MUZ_GC_B4

Axial advance ratio with Glauert correction
= MUZ * VPOV_B4

Mean Performance Parameters, Secondary Gauge Set (B4)

Some of the performance parameters calculated in the previous sections could provide spurious results if instantaneous values of the input parameters are near zero (applicable when one or more of the parameters are in the denominator of the equation). These parameters should be recomputed using only the mean values of the individual inputs. Using LOD_B4 as an example, the new parameter would be

$$\text{LOD_B4_ME} = \text{mean}(\text{LIFT_WE_B4}) / \text{mean}(\text{DEQ_B4})$$

where the result is a single number for each data point (rather than a time history).

The following parameters should be calculated in this way:

ATANXOL_B4_ME
CPOS_ID_B4_ME
CPOS_NI_B4_ME
CPRAT_B4_ME
DEQ_B4_ME
FE_B4_ME
FMERIT_B4_ME
LOD_B4_ME
VOVH_B4_ME
ETAP_B4_ME
ETAP_GC_B4_ME
VPOV_B4_ME
MUZ_GC_B4_ME

For similar reasons, there are tests for divide by zero not explicitly defined in this document.

H Control Angle Calculations

This section provides the equations to calculate 1) the fixed-system control angles (collective and cyclic pitch) assuming zero flapping, 2) the hub flapping in the rotating and non-rotating frame, and 3) the corrected fixed-system control angles accounting for pitch/flap coupling effects.

Fixed-system Control Angles, Primary

The following equations are used to calculate the control system collective, lateral cyclic and longitudinal cyclic pitch using the primary fixed-system actuator displacements as inputs. (these equations are consistent with the updated TTR Control Console equations given in Bell Report 699-616-016 Section 1.20.6, Ref. 16). The same equations will be used with the backup actuator displacements as inputs.

In the equations below, actuators 1, 2, and 3 (labeled A, B, and C on the rig) are physically located at azimuth locations 90°, 210°, and 330°, respectively, measured from the aft position in degrees (0° azimuth angle defined to be pointing downstream with the TTR in helicopter mode, positive rotation clockwise when looking toward the rotor from the swashplate).

Note: SPCOLL and SPCOLL_B are fixed system linear positions (in), whereas COLL and COLLB are rotating system angles (deg).

Inputs

ACT_A_D Primary Act A LVDT measurement, in
ACT_B_D Primary Act B LVDT measurement, in
ACT_C_D Primary Act C LVDT measurement, in
Positive is retraction (gives positive change in blade pitch)

Constants (from Constants section of this document)

SIGNTABLE T-frame orientation
SIGNROT Rotor rotation direction
PARML Pitch arm length
ACTRAD Fixed actuator radius
RSPRAD Pitch link radius at swashplate
PRAZ_A Collective angle for actuator zero
PLL Pitch link length
RTD Converts radians to degrees
DTR Converts degrees to radians
PARAD Pitch arm radius
PSIARM Pitch arm geometry angle
PSICA Swashplate angle

Geometry Calculations for Swashplate Angles

$$\begin{aligned} \text{SPCOLL} &= (\text{ACT_A_D} + \text{ACT_B_D} + \text{ACT_C_D})/3.0 \\ \text{SPLONG} &= \text{RTD} * \text{SIGNTABLE} * \text{ARCSIN}[(\text{ACT_B_D} - \text{ACT_C_D}) / \\ &\quad (2 * \text{ACTRAD} * \text{SIN}(60 * \text{DTR}))] \\ \text{SPLAT} &= \text{RTD} * \text{SIGNTABLE} * \text{SIGNROT} * \text{ARCSIN}[(\text{ACT_A_D} - (\text{ACT_B_D} + \\ &\quad \text{ACT_C_D})/2) / (\text{ACTRAD} * (1 + \text{COS}(60 * \text{DTR})))] \\ \text{SPA1} &= \text{SPLONG} * \text{SIN}(\text{PSICA} * \text{DTR}) + \text{SPLAT} * \text{COS}(\text{PSICA} * \text{DTR}) \\ \text{SPB1} &= \text{SPLONG} * \text{COS}(\text{PSICA} * \text{DTR}) - \text{SPLAT} * \text{SIN}(\text{PSICA} * \text{DTR}) \end{aligned}$$

Where

SPCOLL Swashplate collective position, in
SPLAT Swashplate lateral input, deg
SPLONG Swashplate longitudinal input, deg
SPA1 Swashplate A1, deg
SPB1 Swashplate B1, deg

Note: SPCOLL is set to zero at the reference position.

Geometry Calculations for Swashplate Displacement

$$\begin{aligned} \text{D000} &= \text{SPCOLL} - \text{SIN}(\text{SPA1} * \text{DTR}) * \text{RSPRAD} \\ \text{D090} &= \text{SPCOLL} - \text{SIN}(\text{SPB1} * \text{DTR}) * \text{RSPRAD} \\ \text{D180} &= \text{SPCOLL} + \text{SIN}(\text{SPA1} * \text{DTR}) * \text{RSPRAD} \\ \text{D270} &= \text{SPCOLL} + \text{SIN}(\text{SPB1} * \text{DTR}) * \text{RSPRAD} \end{aligned}$$

Where

Dxxx Swashplate displacement at xxx deg azimuth, in

Control Angle Calculations Using Motion Iteration Loop

Initialization Values:

$$\begin{aligned} \text{ALPHAZERO} &= \text{ARCSIN}[(\text{RSPRAD} - \\ &\quad \text{PARAD}) * \text{ABS}(\text{SIN}(\text{PSIARM} * \text{DTR})) / \text{PLL}] \\ \text{ALPHA000} &= \text{ALPHAZERO} \\ \text{ALPHA090} &= \text{ALPHAZERO} \\ \text{ALPHA180} &= \text{ALPHAZERO} \\ \text{ALPHA270} &= \text{ALPHAZERO} \end{aligned}$$

NITER = 3 = Number of iterations

$$\begin{aligned} &\text{BEGIN ITERATION: (FOR I=1 TO NITER)} \\ \text{TH000} &= \text{ARCSIN}[(\text{D000} - \text{PLL} * (\text{COS}(\text{ALPHAZERO}) - \text{COS}(\text{ALPHA000}))) / \text{PARML}] \\ \text{TH090} &= \text{ARCSIN}[(\text{D090} - \text{PLL} * (\text{COS}(\text{ALPHAZERO}) - \text{COS}(\text{ALPHA090}))) / \text{PARML}] \\ \text{TH180} &= \text{ARCSIN}[(\text{D180} - \text{PLL} * (\text{COS}(\text{ALPHAZERO}) - \text{COS}(\text{ALPHA180}))) / \text{PARML}] \\ \text{TH270} &= \text{ARCSIN}[(\text{D270} - \text{PLL} * (\text{COS}(\text{ALPHAZERO}) - \text{COS}(\text{ALPHA270}))) / \text{PARML}] \end{aligned}$$

$$\begin{aligned} \text{ALPHA000} &= \text{ARCSIN}[\text{SIN}(\text{ALPHAZERO}) + [\text{ABS}(\text{PARML}) / \text{PLL}] * (1 - \text{COS}(\text{TH000}))] \\ \text{ALPHA090} &= \text{ARCSIN}[\text{SIN}(\text{ALPHAZERO}) + [\text{ABS}(\text{PARML}) / \text{PLL}] * (1 - \text{COS}(\text{TH090}))] \end{aligned}$$

$ALPHA180 = ARCSIN[SIN(ALPHAZERO)+[ABS(PARML)/PLL]*(1-COS(TH180))]$
 $ALPHA270 = ARCSIN[SIN(ALPHAZERO)+[ABS(PARML)/PLL]*(1-COS(TH270))]$
 END ITERATION

Note: THxxx and ALPHAxix are in radians.

The final results of these iterations are the swashplate position and fixed-system control angles. Only the following parameters need to be stored and made available for plotting. SPCOLL is used in Section I and as input for a Safety of Flight Data Acquisition System (SofDAS) derived parameter.

SPCOLL

Swashplate collective position, defined above

COLL

Collective angle at 3/4 radius, deg
 $= [(TH000 + TH090 + TH180 + TH270)/4] * RTD + COLLN$

A1

Lateral cyclic angle, deg
 $= -[(TH000 - TH180)/2] * RTD$

B1

Longitudinal cyclic angle, deg
 $= -[(TH090 - TH270)/2] * RTD$

Fixed-system Control Angles, Backup

The calculation of these parameters follow the same process used in Section “Primary Fixed-system Control Angles,” except for using different input parameters:

Inputs

ACT_A_DB	Secondary Act A LVDT measurement, backup, in
ACT_B_DB	Secondary Act B LVDT measurement, backup, in
ACT_C_DB	Secondary Act C LVDT measurement, backup, in

$SPCOLL_B = (ACT_A_DB + ACT_B_DB + ACT_C_DB) / 3$
 Swashplate collective position, in

COLLB

Collective angle at 3/4 radius, deg

A1B

Lateral cyclic angle, deg

B1B

Longitudinal cyclic angle, deg

Rotating System Gimbal and Pitch Angles from Hub Measurements

These equations calculate the hub gimbals angles from the rotating RVDT's attached to the hub linkages. The conversion of RVDT angle to hub flapping/gimbal angle was originally determined using kinematic/geometric equations and verified by test during model checkout. This geometric relationship was ultimately found to be accurately estimated using a 2nd order curve fit on RVDT angle; this curve fit will be used in these equations for simplicity.

Inputs

HB_FLAP_RB_M Hub flap RVDT angle, red blade, deg
HB_FLAP_GRNB_M Hub flap RVDT angle, green blade, deg

Derived parameter, from Section I

AZ Blade 1 Azimuth angle, deg

HB_FLAP_RB

Hub flap angle, red blade, deg
$$= 0.002303 * (HB_FLAP_RB_M)**2 + 0.39797 * HB_FLAP_RB_M - 2.86945$$

HB_FLAP_GRNB

Hub flap angle, green blade, deg
$$= 0.002303 * (HB_FLAP_GRNB_M)**2 + 0.39797 * HB_FLAP_GRNB_M - 2.86945$$

The following equations convert the rotating hub flap angles into fixed system gimbals angles (lateral and longitudinal flapping). The red blade is aligned with the master spline. The green blade has the backup sensor. The green blade lags the red blade by 120 deg = 2.094 radians.

LNGGIM_RF

Gimbal longitudinal flap angle, red blade, fixed system, deg
$$= HB_FLAP_RB * SIN(AZ * DTR)$$

LATGIM_RF

Gimbal lateral flap angle, red blade, fixed system, deg
$$= HB_FLAP_RB * COS(AZ * DTR)$$

LNGGIM_GF

Gimbal longitudinal flap angle, green blade, fixed system, deg
$$= HB_FLAP_GRNB * SIN(AZ * DTR - 2.094)$$

LATGIM_GF

Gimbal lateral flap angle, green blade, fixed system, deg
$$= HB_FLAP_GRNB * COS(AZ * DTR - 2.094)$$

I Hub Loads from Rotating Measurements

The following equations are used to transform the rotating shaft bending measurements to rotating- and fixed-system hub loads. Control system measurements are then used to determine the hub load components coming through the control system. In the future, these two hub load components could be combined to determine the total hub loads (including weight and aero tares) and could then be directly compared to loads from the rotor balance.

Rotating Forces and Moments from Shaft Bending Gauges, Hub Axis

The following equations are used to transform the rotating shaft bending measurements to rotating loads at the hub. Also included in the equations below are correction terms for each of the shaft bending measurements to account for discrepancies/uncertainties with the calibration coefficients for each gauge set.

The shaft bending station numbers reflect the distance (inches) between the top of the mast and the gauge. The rotor hub centerline is 7.21 in below the top of the mast. The driver counterweight attaches 18.24 in below the top of the mast. For reference, the torsion gauges are 12.25 in below the top of the mast.

Constants

LLO	= 2.774 ft	Distance from lower gauges to hub center
LUP	= 0.337 ft	Distance from upper gauges to hub center
LUP_B	= 0.803 ft	Distance from upper gauges to hub center (backup)
CLOPL	= 1.00	Correction term for lower parallel gauge
CLOPR	= 1.00	Correction term for lower perpendicular gauge
CUPPL	= 1.00	Correction term for upper parallel gauge
CUPPR	= 1.00	Correction term for upper perpendicular gauge
CUPPL_B	= 1.00	Correction term for upper parallel gauge (backup)
CUPPR_B	= 1.00	Correction term for upper perpendicular gauge (backup)

Inputs (DAS Tagnames); azimuth is referenced to Master Spline

MST_STA11PLB	Mast Bending Parallel Sta 11.25 (0°), in-lb
MST_STA11PRPB	Mast Bending Perp Sta 11.25 (90°), in-lb
MST_STA16PLB	Mast Bending Parallel Sta 16.85 (0°) (backup), in-lb
MST_STA16PRPB	Mast Bending Perp Sta 16.85 (90°) (backup), in-lb
MST_STA40PLB	Mast Bending Parallel Sta 40.5 (0°), in-lb
MST_STA40PRPB	Mast Bending Perp Sta 40.5 (90°), in-lb

Only one set of hub load parameters is defined here; LUP_B, MST_STA16PLB, and MST_STA16PRPB are backups listed only for possible future use. There are no backups for the lower gauges.

The positive sign convention for the Parallel bending moment gauges is “nose down” at azimuth = 0 deg. The positive sign convention for the Perpendicular gauges is “nose up” at azimuth = 90 deg.

ROTxxx_B etc. were originally intended as backup measurements. They are less accurate than the standard measurements (ROTxxx_A) because the moment arm is shorter, hence more sensitive to any dimensional error. However, the backup values do not include loads from the swashplate linkage or counterweight, and are therefore more representative of pure rotor loads. There are no backups for the lower gauges.

ROTFPL_A

Rotating Force parallel to master spline, lb, positive forward at AZ=0 deg

$$=((\text{CLOPL} * \text{MST_STA40PLB} - \text{CUPPL} * \text{MST_STA11PLB}) / 12) / (\text{LLO} - \text{LUP})$$

ROTFPR_A

Rotating Force perpendicular to master spline, lb, positive aft at AZ=90 deg

$$=(-\text{CUPPR} * \text{MST_STA11PRPB} + \text{CLOPR} * \text{MST_STA40PRPB}) / 12) / (\text{LLO} - \text{LUP})$$

ROTMPL_A

Rotating Moment parallel to master spline, ft-lb, positive nose up at AZ=90 deg

$$=((\text{CUPPR} * \text{MST_STA11PRPB} * \text{LLO} - \text{CLOPR} * \text{MST_STA40PRPB} * \text{LUP}) / 12) / (\text{LLO} - \text{LUP})$$

ROTMPR_A

Rotating Moment perpendicular to master spline, ft-lb, positive nose down at AZ=0 deg

$$=((\text{CUPPL} * \text{MST_STA11PLB} * \text{LLO} - \text{CLOPL} * \text{MST_STA40PLB} * \text{LUP}) / 12) / (\text{LLO} - \text{LUP})$$

ROTFPL_B

Rotating Force parallel to master spline (backup), lb, positive forward at AZ= 0 deg

$$=((\text{CUPPL_B} * \text{MST_STA16PLB} - \text{CUPPL} * \text{MST_STA11PLB}) / 12) / (\text{LUP_B} - \text{LUP})$$

ROTFPR_B

Rotating Force perpendicular to master spline (backup), lb, positive aft at AZ=90 deg

$$=(-\text{CUPPR_B} * \text{MST_STA11PRPB} + \text{CUPPR_B} * \text{MST_STA16PRPB}) / 12) / (\text{LUP_B} - \text{LUP})$$

ROTMPL_B

Rotating Moment parallel to master spline (backup), ft-lb, positive nose up at AZ=90 deg

$$=((\text{CUPPR} * \text{MST_STA11PRPB} * \text{LUP_B} - \text{CUPPR_B} * \text{MST_STA16PRPB} * \text{LUP}) / 12) / (\text{LUP_B} - \text{LUP})$$

ROTMPR_B

Rotating Moment perpendicular to master spline (backup), ft-lb, positive nose down at AZ=0 deg

$$= ((\text{CUPPL} * \text{MST_STA11PLB} * \text{LUP_B} - \text{CUPPL_B} * \text{MST_STA16PLB} * \text{LUP}) / 12) / (\text{LUP_B} - \text{LUP})$$

Fixed-system Forces and Moments from Shaft Bending Gauges, Hub Axis

The following equations are used to transform the rotating hub forces and moments to fixed system hub forces and moments. Weight and aerodynamic tares are then applied to get fully corrected loads.

Inputs

SCANNO Scan number of current sample, 1 to NPR

Constants

NPR = 256 Data points per revolution
DTR Degrees to radians (from Constants)

AZ

Blade 1 Azimuth angle, deg
= ((SCANNO-1) / NPR)*360

Uncorrected Shaft Loads, Fixed System Hub Axis

AF_UNC_SH_A

Axial Force from shaft gauges, lb, positive starboard
= -ROTFPL_A * COS(AZ * DTR) + ROTFPR_A * SIN(AZ * DTR)

SF_UNC_SH_A

Side Force from shaft gauges, lb, positive down
= -ROTFPL_A * SIN(AZ * DTR) - ROTFPR_A * COS(AZ * DTR)

PM_UNC_SH_A

Pitching Moment from shaft gauges, ft-lb, positive nose right
= ROTMPL_A * SIN(AZ * DTR) - ROTMPR_A * COS(AZ * DTR)

RM_UNC_SH_A

Rolling Moment from shaft gauges, ft-lb, positive nose down
= -ROTMPL_A * COS(AZ * DTR) - ROTMPR_A * SIN(AZ * DTR)

AF_UNC_SH_B

Axial Force from upper shaft gauges (backup), lb, positive starboard
= -ROTFPL_A * COS(AZ * DTR) + ROTFPR_A * SIN(AZ * DTR)

SF_UNC_SH_B

Side Force from upper shaft gauges (backup), lb, positive down
= -ROTFPL_B * SIN(AZ * DTR) - ROTFPR_B * COS(AZ * DTR)

PM_UNC_SH_B

Pitching Moment from upper shaft gauges (backup), ft-lb, positive nose right
= ROTMPL_B * SIN(AZ * DTR) - ROTMPR_B * COS(AZ * DTR)

RM_UNC_SH_B

Rolling Moment from upper shaft gauges (backup), ft-lb, positive nose down
 $= -\text{ROTMPL_B} * \text{COS}(\text{AZ} * \text{DTR}) - \text{ROTMPR_B} * \text{SIN}(\text{AZ} * \text{DTR})$

Shaft Load Weight Corrections

Fixed-system weight corrections must be applied before aerodynamic tares are applied. The full vector of rotor shaft weight corrections is defined to accommodate possible future revisions (e.g. results of recalibrations), but only the SF correction is non-zero here.

It is recommended that only the _A gauge data be used, so weight and aero tare corrections are defined here for only the _A tares. The _B parameters use the _A tares. The _A and _B suffixes are accordingly dropped from the tare corrections.

Note: These parameters are not normally stored, but are shown here to clarify the process.

AF_SH_WT

Axial Force weight tare for shaft gauges, lb, positive starboard
 $= 0$

SF_SH_WT

Side Force weight tare for shaft gauges, lb, positive down
 $= 650$

PM_SH_WT

Pitching Moment weight tare for shaft gauges, ft-lb, positive nose right
 $= 0$

RM_SH_WT

Pitching Moment weight tare for shaft gauges, ft-lb, positive nose down
 $= 0$

Shaft Load Aerodynamic Tares

Aerodynamic tares are defined only in the range $0 \leq \Psi \leq 110$ deg and are set to zero elsewhere.

AFATR_SH

Aero tare with rotating spinner for shaft axial force, positive starboard, lb

```
IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN
  AFATR_SH = 0.0
ELSE IF (TT_YAW_C ≤ 90) THEN
  AFATR_SH = -1.44E-05 * Q * (TT_YAW_C)**3 + 2.15E-03 * Q *
  TT_YAW_C**2 + 0.168 * Q * (TT_YAW_C)
ELSE
  AFATR_SH = 6.62E-03 * Q * (TT_YAW_C)**2 - 1.44 * Q *
  (TT_YAW_C) + 80.7 * Q
ENDIF
ENDIF
```

SFATR_SH

Aero tare with rotating spinner for shaft side force, positive down, lb

```
IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN
  SFATR_SH = 0.0
ELSE IF (TT_YAW_C < 90) THEN
  SFATR_SH = -28.9 * VKTS * N(TT_YAW_C;76.5,9.23)
ELSE
  SFATR_SH = -2.25E-03 * VKTS * (TT_YAW_C)**2 + 0.441 *
  VKTS * (TT_YAW_C) - VKTS * 22.6
ENDIF
ENDIF
```

where $N(x; \mu, \sigma)$ is the probability density function with normal distribution, $\mu = 76.5$ deg, $\sigma = 9.23$ deg, and scale factor = -28.9. Note that SFATR depends upon V (knots), not Q (lb/ft²).

PMATR_SH

Aero tare with rotating spinner for shaft pitching moment, positive nose right, ft-lb

```
IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN
  PMATR_SH = 0.0
ELSE IF (TT_YAW_C ≤ 90) THEN
  PMATR_SH = 2.44E-07 * Q * (TT_YAW_C)**3 - 2.98E-03 * Q *
  (TT_YAW_C)**2 + 0.324 * Q * (TT_YAW_C)
ELSE
  PMATR_SH = 1.04E-02 * Q * (TT_YAW_C)**2 - 2.18 * Q *
  (TT_YAW_C) + 116 * Q
ENDIF
ENDIF
```

The cubic term in the first equation (2.44e-07) could be set = 0 with negligible effect on accuracy. It has been left in this form to match the coding for the rotor balance aero tare PMATR.

RMATR_SH

Aero tare with rotating spinner for shaft rolling moment, positive nose down, ft-lb

IF (TT_YAW_C < 1 .OR. TT_YAW_C > 111) THEN

 RMATR_SH = 0.0

ELSE IF (TT_YAW_C < 90) THEN

 RMATR_SH = -21.1 * VKTS * N(TT_YAW_C; 77.9,10.64)

ELSE

 RMATR_SH = -1.61E-03 * VKTS * (TT_YAW_C)**2 + 0.312 *
 VKTS * (TT_YAW_C) - 16.5 * VKTS

ENDIF

ENDIF

where $N(x; \mu, \sigma)$ is the probability density function with normal distribution, $\mu = 77.9$ deg, $\sigma = 10.64$ deg, and scale factor = -21.1. Note that PMATR depends upon V (knots), not Q (lb/ft²).

Shaft Loads Corrected for Weight Tares

This section corrects the xx_UNC_SH_A loads for the effects of weight tares.

AF_SH_CWT_A

Weight tare corrected shaft Axial Force, lb

= AF_UNC_SH_A - AF_SH_WT

SF_SH_CWT_A

Weight tare corrected shaft Side Force, lb

= SF_UNC_SH_A - SF_SH_WT

PM_SH_CWT_A

Weight tare corrected shaft Pitching Moment, ft-lb

= PM_UNC_SH_A - PM_SH_WT

RM_SH_CWT_A

Weight tare corrected shaft Roll Moment, ft-lb

= RM_UNC_SH_A - RM_SH_WT

AF_SH_CWT_B

Weight tare corrected shaft Axial Force, lb

= AF_UNC_SH_B - AF_SH_WT

SF_SH_CWT_B

Weight tare corrected shaft Side Force, lb

= SF_UNC_SH_B - SF_SH_WT

PM_SH_CWT_B

Weight tare corrected shaft Pitching Moment, ft-lb
 = PM_UNC_SH_B – PM_SH_WT

RM_SH_CWT_B

Weight tare corrected shaft Roll Moment, ft-lb
 = RM_UNC_SH_B – RM_SH_WT

Shaft Loads Corrected for Aerodynamic Tares

This section corrects the xx_SH_CWT loads for the effects of aerodynamic tares (determined with the rotor-off weight tare removed). If VKTS < 5 kts (hover data), then the aerodynamic tares are assumed to be zero. The resulting loads are in the BD axis system.

AF_BD_SH_A

Weight and aero tare corrected shaft Axial Force, positive starboard, lb
 = AF_SH_CWT_A – AFATR_SH

SF_BD_SH_A

Weight and aero tare corrected shaft Side Force, positive down, lb
 = SF_SH_CWT_A – SFATR_SH

PM_BD_SH_A

Weight and aero tare corrected shaft Pitching Moment, positive nose right, ft-lb
 = PM_SH_CWT_A – PMATR_SH

RM_BD_SH_A

Weight and aero tare corrected shaft Rolling Moment, positive nose down, ft-lb
 = RM_SH_CWT_A – RMATR_SH

AF_BD_SH_B

Weight and aero tare corrected shaft Axial Force, positive starboard, lb
 = AF_SH_CWT_B – AFATR_SH

SF_BD_SH_B

Weight and aero tare corrected shaft Side Force, positive down, lb
 = SF_SH_CWT_B – SFATR_SH

PM_BD_SH_B

Weight and aero tare corrected shaft Pitching Moment, positive nose right, ft-lb
 = PM_SH_CWT_B – PMATR_SH

RM_BD_SH_B

Weight and aero tare corrected shaft Rolling Moment, positive nose down, ft-lb
 = RM_SH_CWT_B – RMATR_SH

Fixed-system Forces and Moments from Control Loads, Hub Axis

The following are the components of fixed-system hub loads due to the control system loads as derived from (1) the stationary control actuators (aka “pushrods”), (2) the swashplate via the support tube, and (3) the rotating pitch links. Actuators A, B, and C are located at fixed-system azimuth locations 90°, 210°, and 330°, respectively, all referenced to the balance axis system (0° is horizontal oriented aft in helicopter mode, and 90° is vertical oriented down). The actuator forces are positive in tension and are approximately parallel to the rotor shaft; a correction factor adjusts for non-parallel effects at mid-stroke position. (The difference between the extremes of the actuator stroke is much less than the accuracy of the balance, so a fixed correction is adequate.) The correction should *not* be applied to actuator SOF limits.

The swashplate anti-drive assembly (aka “stationary scissors”) load is located at azimuth 30 deg and radius of 14.41 in (minimum collective, per Bell Report 699-616-004 Vol. 2, Ref. 7; Bell dwg 699-616-511); this is used to determine the axial and side forces from the control system. The swashplate rides on the support tube, which has bending gauges at the bottom. These gauges are used to measure the bending moments from the control system.

Blade aerodynamic pitch is defined as the angle between the chord line and the plane of rotation, taken at 75% radius (117.00 in). Blade pitch and collective angles should be nearly equal. Because of blade twist, 0-deg chord angle at 0.75R (117.00 in radius) is -15 deg at the pitch horn (2.83 in radius). The control console is calibrated with the pitch horn level in order to reduce nonlinear effects. See also COLLN.

Warning: Bell drawings and documents may use a different zero reference for pitch and collective, which should be explicitly checked.

0 deg azimuth is aligned with the rotor mast master spline and the red blade pitch axis, with the red blade horizontal (Fig. 3).

The rotating pitch link load for blade 1 (Red) is assumed parallel to the mast at a pitch horn radius of 10.897 in and acting at an azimuth 75 deg CW (trailing) from the zero-azimuth reference with pitch horns level. The other pitch links are assumed to be located at increments of 120 deg from this blade 1 position: in the direction of rotation, blade 2 (White) is at 120 deg and blade 3 (Green) is at 240 deg. Pitch link forces are positive in tension.

The control loads induced by the weight of the swashplate are accounted for in the balance tare calculations. Alternative calculations are included here for diagnostics.

Inputs

CTRL_ACT_A_AX	Stationary Control Actuator A load, lb
CTRL_ACT_B_AX	Stationary Control Actuator B load, lb
CTRL_ACT_C_AX	Stationary Control Actuator C load, lb
REDPTCHLK_AX	Pitch Link 1 force, lb
WHTPTCHLK_AX	Pitch Link 2 force, lb
GRNPTCHLK_AX	Pitch Link 3 force, lb
SWTB_LATB	Swashplate guide tube lateral bending, in-lb
SWTB_FAB	Swashplate guide tube fore/aft bending, in-lb

Derived parameter from Section K:

SWANTDR_SHEAR Anti-drive (stationary scissors) load, lb

Constants from Section B:

ACTRAD	Actuator radius, in
C_ACTLD	Correction factor for actuator load
RSPRAD	Pitch link radius at swashplate, in
PRAZ_A	Sta. Actuator A azimuth position, deg
PRAZ_B	Sta. Actuator B azimuth position, deg
PRAZ_C	Sta. Actuator C azimuth position, deg
PLAZ_1	Pitch link 1 azimuth position, deg
SSCAZ	Sta. Scissors azimuth position, deg
DTR	Degrees to radians, rad/deg

Note: pitch link loads are NOT here corrected for variations in cant angle as blade pitch changes. PLAZ_1 varies slightly with blade pitch, hence with azimuth for non-zero cyclic control. Forces and moments due to pitch link loads vary slightly with cant angle, which also varies with blade pitch. These variations change only with control inputs and can therefore be corrected post-test.

NF_BD_PR

Normal Force from sta. control loads, lb
= C_ACTLD * (CTRL_ACT_A_AX + CTRL_ACT_B_AX +
CTRL_ACT_C_AX)

AF_BD_PR

Axial Force from sta. control loads, lb
= -SWANTDR_SHEAR * SIN(SSCAZ * DTR)

SF_BD_PR

Side Force from sta. control loads, lb
= SWANTDR_SHEAR * COS(SSCAZ * DTR)

PM_BD_PR

Pitching Moment from sta. control loads, ft-lb
= -C_ACTLD * ACTRAD / 12 * [CTRL_ACT_B_AX * COS(PRAZ_B * DTR)
+ CTRL_ACT_C_AX * COS(PRAZ_C * DTR)]

RM_BD_PR

Rolling Moment from sta. control loads, ft-lb
= -C_ACTLD * ACTRAD / 12 * [CTRL_ACT_A_AX +
CTRL_ACT_B_AX * SIN(PRAZ_B * DTR) +
CTRL_ACT_C_AX * SIN(PRAZ_C * DTR)]

DEL_3

Delta-3 pitch-flap coupling angle, deg
= ATAN[PARMS / (PARML * COS(COLL - 15))] * RTD

Defined to simplify hub moment equations; includes effect of collective (ignores TORQL, *Bell proprietary*). Keep in database for diagnostics.
Note: COLLN is intended to reference COLL to actuator zero, not level pitch horn, so use explicit -15 deg adjustment here and following.

PARAD_E

Effective pitch arm radius, adjusted for collective, in

$$= \text{SQRT}[\text{PARMS}^2 + (\text{PARML} * \text{COS}((\text{COLL} - 15) * \text{DTR}))^2]$$

Not retained in database; omits TORQL (*Bell proprietary*).

ROTM1PL

Rotating Moment 1 from pitch link loads, ft-lb
= PARAD_E / 12 * [- REDPTCHLK_AX * COS(DEL_3 * DTR)
+ GRNPTCHLK_AX * SIN((30 + DEL_3) * DTR)
+ WHTPTCHLK_AX * SIN((30 - DEL_3) * DTR)]

Moment is referenced to red blade, corrected for delta-3;
moment is right-handed (nose up) looking outward along red blade pitch axis.

ROTM2PL

Rotating Moment 2 from pitch link loads, ft-lb
= PARAD_E / 12 * [REDPTCHLK_AX * SIN(DEL_3 * DTR)
+ GRNPTCHLK_AX * COS((30 + DEL_3) * DTR)
- WHTPTCHLK_AX * COS((30 - DEL_3) * DTR)]

Moment is 90° in direction of rotation from red blade, corrected for delta-3;
moment is right-handed looking outward from hub.

NF_BD_PL

Normal Force from pitch link loads, lb
= REDPTCHLK_AX + WHTPTCHLK_AX + GRNPTCHLK_AX

PM_BD_PL

Pitching Moment from pitch link loads, ft-lb
= ROTM1PL * SIN(AZ * DTR) + ROTM2PL * COS(AZ * DTR)

RM_BD_PL

Rolling Moment from pitch link loads, ft-lb
= -ROTM1PL * COS(AZ * DTR) + ROTM2PL * SIN(AZ * DTR)

RM_BD_PL = -ROTM1PL and PM_BD_PL = ROTM2PL when the red blade is level pointing downstream in helicopter mode (90° yaw).

Swashplate Loads

The following loads are computed for diagnostic purposes. They include weight tares RMWTNRB etc. (Section D), plus dynamic loads.

SWTB_LATB is positive when pushing from 180 to 0 deg azimuth;

SWTB_FAB is positive when pushing from 90 to 270 deg azimuth.

SF_BD_SP

Side Force from swashplate, lb

$$= -\text{SWTB_FAB} / (\text{SPCOLL} + \text{SP_OFFSET})$$

AF_BD_SP

Axial Force from swashplate, lb

$$= \text{SWTB_LATB} / (\text{SPCOLL} + \text{SP_OFFSET})$$

PM_BD_SP

Pitching Moment from swashplate, ft-lb

$$= \text{SWTB_LATB} / 12$$

RM_BD_SP

Rolling Moment from swashplate, ft-lb

$$= \text{SWTB_FAB} / 12$$

J Spinner Loads

To help determine rotor-only forces and moments, it is necessary to account for the non-rotor blade components whose loads are also measured by the rotor balance. This is typically addressed by acquiring aerodynamic tare data without the rotor over a range of conditions (shaft angle, tunnel speed, etc.) and subtracting the loads at similar conditions from the rotor-on measurements (see Sections D-G). For a tiltrotor/propeller with a spinner, however, this approach may not adequately account for the mutual aerodynamic interactions between the rotor, rotor wake and spinner.

For the TTR, three alternative methods are provided for estimating the spinner load. The first is classic aerodynamic tare corrections, e.g. NFATR; see Section D. The second involves the direct measurement of spinner support stresses and subsequent calibration/relationship of these measurements to applied aerodynamic loads. The third involves estimating the axial spinner loads based on the measured pressure inside the spinner.

Depending on the results of the calibration, the second method would ideally provide estimates for 3 forces and 3 moments (instead of just axial load). For this test, however, the second and third methods were determined to be of limited validity. Based on pre-test calibrations, the axial spinner loads can be determined from single strain gauge measurements and are provided as direct measurements (AX_LD_B1 and AX_LD_B2). Such measurements will require corrections for centrifugal loads. Additional load measurements are defined for diagnostic purposes.

Either of the first two methods may require corrections for pressure forces on the front face of the mast module, which will be seen by the balance as an axial load. The mast module pressure force, defined below, will provide diagnostics data for post-test evaluation.

The third method uses the difference between tunnel total pressure and spinner pressure to estimate the axial force on the spinner. Ultimately, the differences between rotor-on and rotor-off measurements can be used to determine the interactional effects. The following section provides the equations to estimate the pressure load.

Spinner Pressures

Inputs

HB_PRESS	Measured pressure inside spinner, psia
PS	Calculated static pressure at tunnel centerline, psfa

Constants

AF_SPINNER = 652 in² Spinner frontal area
Estimated from top ring of controls fairing assembly, Bell dwg. 699-616-528
(D=28.812 in).

AF_MASTMODULE = 552 in² Mast module frontal area
Ref. Triumph drawing 1317-110 (D=26.50 in)

SP_PRESS_FORCE

Spinner axial force from internal pressure, positive in balance NF direction, lb
= AF_SPINNER * (HB_PRESS – PS/144)

MM_PRESS_FORCE

Mast module axial force from internal pressure, positive in NF direction, lb
= AF_MASTMODULE * (HB_PRESS – PS/144)

There is at present only one pressure transducer (HB_PRESS), hence the spinner and mast module pressure forces are in a fixed ratio (652/552). Define both force parameters here for possible future use with additional pressure transducers.

Warning: check HB_PRESS data for drift and scatter before using any derived data.

Spinner Loads from Spoke Strain Gauges

Not all spinner strain gauges were calibrated, and not all calibrations include moment conversions. Only one lower spinner spoke is instrumented. With the existing spoke strain gauges and bench calibrations, it is not possible to correct for significant torsion responses or to measure all contributions to side loads. The spinner moments are intended only for diagnostic purposes, as are most fixed-system loads from individual strain gauges.

Assumptions:

- (1) The lower spoke beam-bending gauges are unreliable because there is no effective beam-wise bending restraint.
- (2) The lower spoke torsion gauges *may* be effective for pure torsion loads because the torsion restraint at the slider would ideally cancel or relieve off-axis loads. However, the slider is not perfect, so cancellation should not be assumed and those torsion gauges may not be accurate.
- (3) Both upper and lower torsion gauges are unlikely to be accurate because of poor load paths. Differential beam-bending gauges could in principle be used to estimate moments, but in the absence of proper calibrations only diagnostic data will be processed.
- (4) The spinner support strain gauges are assumed to be aligned with the pitch axes of their respective blades. This is not literally true for the upper supports.
- (5) The lower spoke chord-bending gauges respond only to pure side loads because the slider relieves any rotational moments caused by imperfectly balanced side forces.

Caveat: There are centrifugal-force effects that are not included here and that may require calibration corrections, likely in the form of offsets dependent on rpm. The bench calibrations (Bell Report 699-616-008, Ref. 17) did not include centrifugal effects.

Inputs

SPUPRSPRT_STA6BB	beam bending at Sta 5.97, Red spoke
AX_LD_B1	total axial load, calibrated to Green spoke gauge
AX_LD_B2	total axial load, calibrated to White spoke gauge
SPUPRSPRT_STA6CB	chord bending at Sta 5.97, Red spoke
SPUPRSPRT_STA9TO_M	torsion at Sta 9.0, Red spoke
SPLWRSPRT_STA5CB	chord bending at Sta 5.0, Red spoke
SPLWRSPRT_STA8TO	torsion at Sta 8.5, Red spoke

Derived parameter from Section I:

AZ	blade 1 azimuth angle, deg
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Constant from Section B:

DTR	degrees to radians
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The following strain gauges are recorded but not used for computed loads:

SPUPRSPRT_GRNCB	chord bending at Sta 5.97, Green spoke *
SPUPRSPRT_WHTCB	chord bending at Sta 5.97, White spoke *
SPUPRSPRT_GRNTOR	torsion at Sta 9.0, Green spoke *
SPUPRSPRT_WHTTOR	torsion at Sta 9.0, White spoke *
SPLWRSPRT_STA5BB	beam bending at Sta 5.0, Red spoke

* Gauges so marked are not calibrated and are recorded as voltages.

Constants

UPR_BMA	= 9.75 in	Upper support beam-bending moment arm
UPR_RAD	= 1.276 ft	Upper support effective radius (measured)

The upper spinner spokes end slightly inboard of the spinner outer surface, hence the radius to the loading point is less than the nominal spinner radius. UPR_BMA is approximately the difference between UPR_RAD and the bridge station (Bell Report 699-616-008 Fig. 43, Ref. 17).

Intermediate Computations

SPUPRSPRT_STA9TO

$$\begin{aligned} & \text{Spinner upper support torsion, station 9.0, coupled calibration, in-lb} \\ & = \text{SPUPRSPRT_STA9TO_M} + 0.01396 * \text{SPUPRSPRT_STA6CB} \\ & \quad - 0.0428 * \text{SPUPRSPRT_STA6BB} \end{aligned}$$

SPLWRSPRT_SLG

Spinner lower support side load, lb
= SPLWRSPRT_STA5CB / 5.00

Ref. Bell Report 699-616-008 Fig. 39 (Ref. 17)

Rotating Loads, in Local Axes

AX_LD_RB

Spinner axial load derived solely from red spoke strain gauge, lb
= $-3 * 2.62 * SPUPRSPRT_STA6BB / UPR_BMA$

This load should be similar to AX_LD_B1 and AX_LD_B2. Different calibration methods were used for SPUPRSPRT and AX_LD_Bn, hence the signs are different. The factor 2.62 was derived from the data in Bell Report 699-616-008 Section 1.3 (Ref. 17). The calibration is not rigorous, but the results should be more consistent and easier to correct later if needed.

SPRAX_LD

Spinner axial load from strain gauges, positive in balance NF direction, lb
= $-(AX_LD_B1 + AX_LD_B2 + AL_LD_RB) / 3$

SPRM_PARA1

Spinner rotating moment from spoke gauges, axis parallel to master spline, ft-lb
= $(AX_LD_B1 - AX_LD_B2) * UPR_RAD * \cos(DTR * 30) / 3$

SPRM_PARA2

Spinner rotating moment from spoke gauges, axis parallel to master spline, ft-lb
= $(AX_LD_B1 - AX_LD_B2) * UPR_RAD * \cos(DTR * 30) / 3$
+ $(SPUPRSPRT_STA9TO + SPLWRSPRT_STA8TO) / 12$

SPRM_PARA2 is more geometrically accurate than SPRM_PARA1, but will have worse signal-to-noise ratio.

SPRM_PERP

Spinner rotating moment from spoke gauges, perpendicular to master spline, ft-lb
= $[(AX_LD_B1 + AX_LD_B2) / 2 - AX_LD_RB] * UPR_RAD / 3$

Literally = $(AX_LD_B1 + AX_LD_B2) * UPR_RAD * \sin(DTR * 30) / 3$
- $AX_LD_RB * UPR_RAD / 3$; use simplified equation above.

SPRM_PERP does not include contributions from the uncalibrated torsion gauges. If SPRM_PARA1 gives poor results, then SPRM_PERP should not be relied upon.

SPRF_PERP

Spinner rotating side force from strain gauges, perpendicular to master spline, lb
= $SPLWRSPRT_SLG + SPUPRSPRT_STA6CB / 5.97$

The opposite-side chord gauges are inactive, so the active gauges measure approximately half of the total force. However, the Bell strap calibration was to full load and the chord gauge calibration coefficients are set accordingly.

Fixed-System Loads, in Hub Axes

AF_BA_SP

Spinner Axial Force from strain gauges, lb
 $= 2 * SPRF_PERP * COS(AZ * DTR)$

SF_BA_SP

Spinner Side force from strain gauges, lb
 $= 2 * SPRF_PERP * SIN(AZ * DTR)$

PM_BA_SP1

Spinner Pitching Moment from strain gauges, ft-lb
 $= SPRM_PARA1 * SIN(AZ * DTR) + SPRM_PERP * COS(AZ * DTR)$

RM_BA_SP1

Spinner Rolling Moment from strain gauges, ft-lb
 $= -SPRM_PARA1 * COS(AZ * DTR) + SPRM_PERP * SIN(AZ * DTR)$

PM_BA_SP2

Spinner Pitching Moment from strain gauges, ft-lb
 $= SPRM_PARA2 * SIN(AZ * DTR) + SPRM_PERP * COS(AZ * DTR)$

RM_BA_SP2

Spinner Rolling Moment from strain gauges, ft-lb
 $= -SPRM_PARA2 * COS(AZ * DTR) + SPRM_PERP * SIN(AZ * DTR)$

None of these fixed-system spinner loads are reliable, because the strain gauge data are of poor quality or important gauges are inactive. Moment calculations do not include contributions from uncalibrated torsion gauges and so are not geometrically exact. PM_BA_SP2 and RM_BA_SP2 include calibrated torsion gauges on the red-blade spokes and are therefore a little more accurate than PM_BA_SP1 and RM_BA_SP1, but are geometrically incomplete and will have worse signal-to-noise ratio.

K Derived Parameters from Rotor Measurements

This section provides parameters derived from miscellaneous rotor measurements. These derived parameters range from simple unit conversions to revised loads based on coupled calibrations. The parameters defined here closely parallel those in Section L, but are processed differently. In particular, the means, peak values, etc. are here computed for an exact integer number of rotor revolutions and should therefore be more accurate than the computations of Section L. See the beginning of Section L for further discussion. Parameters are given the same names in Sections K and L if they are defined identically, but with extra suffixes in Section L.

Inputs

HB_ACCELX	X-Axis accelerometer in the instrumentation hat, g
HB_ACCELZ	Z-Axis accelerometer in the instrumentation hat, g
MST_STA11PLB	Mast bending parallel station 11.25, in-lb
MST_STA11PRPB	Mast bending perpendicular station 11.25, in-lb
MST_STA11TO	Mast torsion station 11.25, in-lb
MST_STA16PLB	Mast bending parallel station 16.85, in-lb
MST_STA16PRPB	Mast bending perpendicular station 16.85, in-lb
REDY_STA12BB_M	Measured red yoke beam bending, station 12.75, in-lb
REDINBDSPNDL_BS	Red inboard spindle beam shear, lb
REDY_STA12CB_M	Measured red yoke chord bending, station 12.75, in-lb
REDINBDSPNDL_CS	Red inboard spindle chord shear, lb
SWANTDR_SHEAR_M	Measured anti-drive link shear force, positive slope, lb
SWTB_LATB	Swashplate guide tube lateral bending, in-lb
SWTB_FAB	Swashplate guide tube fore/aft bending, in-lb
SPCOLL	Swashplate collective position, in

Swashplate Loads

Constant from Section B:

SP_OFFSET

Offset between zero actuator reference and swashplate support tube gauges, in
Determined during control console calibration. (See also COLLN.)

Swashplate Support Tube and Anti-Drive Link

SWTB_NETB

Support tube net bending moment, in-lb
 $= \text{SQRT}(\text{SWTB_LATB}^{**2} + \text{SWTB_FAB}^{**2})$

For each revolution, determine the mean values of SWTB_LATB and SWTB_FAB:
SWTB_LATB_MN and SWTB_FAB_MN

Compute the net vibratory bending moment:

$$\text{SWTB_NETB_V} = \text{SQRT}[(\text{SWTB_LATB} - \text{SWTB_LATB_MN})^{**2} + (\text{SWTB_FAB} - \text{SWTB_FAB_MN})^{**2}]$$

SWANTDR_SHEAR

Anti-drive link shear force, accounting for bi-directional slopes, lb
= SWANTDR_SHEAR_M if SWANTDR_SHEAR_M is >= 0
= 1.346 * SWANTDR_SHEAR_M if SWANTDR_SHEAR_M is < 0

Computations assume measurement EU was determined using positive slope.

For each revolution, determine the mean value of SWANTDR_SHEAR_MN

SWTB_STRESS

Support tube stress location 1, psi
= 0.45 * SWTB_NETB + 11.97 * ABS(SWANTDR_SHEAR)

Compute the net vibratory stresses:

$$\text{SWTB_STRESS_V} = 0.45 * \text{SWTB_NETB_V} + 11.97 * \text{ABS}(\text{SWANTDR_SHEAR} - \text{SWANTDR_SHEAR_MN})$$

Ref. Bell Report 699-616-004 Vol. I, Section 4.2.11 (Ref. 7) and Bell spreadsheet “Support Tube Plate and Bolts – Stress Equation”

Swashplate Tube Support Plate

SWTB_SP

Swashplate tube support plate stress, psi
= 0.49 * SWTB_NETB + 8.05 * ABS(SWANTDR_SHEAR)

Compute the net vibratory stress:

$$\text{SWTB_SP_V} = 0.49 * \text{SWTB_NETB_V} + 8.05 * \text{ABS}(\text{SWANTDR_SHEAR} - \text{SWANTDR_SHEAR_MN})$$

Ref. Bell Report 699-616-004 Vol. I, Section 4.2.12 (Ref. 7) and Bell spreadsheet “Support Tube Plate and Bolts – Stress Equation Rev F”

Swashplate Tube Support Plate Bolts

SWTB_BOLT1

Swashplate tube support plate bolt shear stress, psi
= 0.061 * SWTB_NETB + 4.196 * ABS(SWANTDR_SHEAR)

SWTB_BOLT2

$$\begin{aligned} & \text{Swashplate tube support plate bolt tensile stress, psi} \\ & = 0.65 * \text{SWTB_NETB} + 10.09 * \text{ABS}(\text{SWANTDR_SHEAR}) \end{aligned}$$

The coefficients assume that SWTB_NETB has units of in-lb and SWANTDR_SHEAR has units of lb. (SWTB_BOLT1 is always less than SWTB_BOLT2, but has a lower limit.)

Compute the net vibratory stresses:

$$\begin{aligned} \text{SWTB_BOLT1_V} &= 0.061 * \text{SWTB_NETB_V} \\ &+ 4.196 * \text{ABS}(\text{SWANTDR_SHEAR} - \text{SWANTDR_SHEAR_MN}) \end{aligned}$$

$$\begin{aligned} \text{SWTB_BOLT2_V} &= 0.65 * \text{SWTB_NETB_V} \\ &+ 10.09 * \text{ABS}(\text{SWANTDR_SHEAR} - \text{SWANTDR_SHEAR_MN}) \end{aligned}$$

Ref. Bell spreadsheet “Support Tube Plate and Bolts – Stress Equation”

Swashplate Shear

Swashplate shear load is a function of swashplate collective position. Collective position SPCOLL will change much more slowly than the buffer update rate, so the value provided via BDAS is adequate.

SPSHEAR

$$\begin{aligned} & \text{Swashplate shear load, lb} \\ & = \text{SWTB_NETB} / (\text{SPCOLL} + \text{SP_OFFSET}) \end{aligned}$$

Compute the net vibratory load:

$$\text{SPSHEAR_V} = \text{SWTB_NETB_V} / (\text{SPCOLL} + \text{SP_OFFSET})$$

Mast Loads

Instrumentation Plate and Adapter

The hub accelerometers monitor both the instrumentation plate and the plate adapter. The plate has the lower limit. The acceleration limit depends on the weight of the instrumentation hat.

HUB_ACCEL

$$\begin{aligned} & \text{Net hub acceleration, g} \\ & = \text{SQRT}((\text{HB_ACCELX})^{**2} + \text{HB_ACCELZ})^{**2}) \end{aligned}$$

For each revolution, determine the mean values of HB_ACCELX and HB_ACCELZ:
HB_ACCELX_MN and HB_ACCELZ_MN

Compute the net vibratory hub acceleration:

$$\text{HUB_ACCEL_V} = \text{SQRT}[(\text{HB_ACCELX} - \text{HB_ACCELX_MN})^{**2} + \text{HB_ACCELZ} - \text{HB_ACCELZ_MN})^{**2}]$$

Ref. Bell Report 699-616-004 Vol. II, Sections 3.3.39.4 & 3.3.40.4 (Ref. 7).

Proprotor Mast Derived Parameters for Monitoring

Ref. Bell spreadsheet "609-040-315 Mast 3-7-2017 update"

MST_STA11STRS

Mast Sta 11.25 stress, psi

$$= \text{SQRT}[(0.288 * \text{NFBAL} + 0.4024 * \text{SQRT}(\text{MST_STA11PRPB}^{**2} + \text{MST_STA11PLB}^{**2}))^{**2} + 3 * (0.2012 * \text{MST_STA11TO})^{**2}]$$

MST_STA16STRS

Mast Sta 16.85 stress, psi

$$= \text{SQRT}(0.2634 * \text{NFBAL} + 0.3657 * \text{SQRT}(\text{MST_STA16PRPB}^{**2} + \text{MST_STA16PLB}^{**2}))^{**2} + 3 * (0.1829 * \text{MST_STA11TO})^{**2}]$$

For each revolution, determine the mean values of NFBAL, MST_STA11PRPB, MST_STA11PLB, MST_STA11TO, MST_STA16PRPB, and MST_STA16PL:

NFBAL_MN, MST_STA11PRPB_MN, MST_STA11PLB_MN, MST_STA11TO_MN, MST_STA16PRPB_MN, MST_STA16PLB_MN

Compute the net vibratory stresses:

$$\text{MST_STA11STRS_V} = \text{SQRT}[(0.2887 * (\text{NFBAL} - \text{NFBAL_MN}) + 0.4024 * \text{SQRT}((\text{MST_STA11PRPB} - \text{MST_STA11PRPB_MN})^{**2} + (\text{MST_STA11PLB} - \text{MST_STA11PLB_MN})^{**2}))^{**2} + 3 * (0.2012 * (\text{MST_STA11TO} - \text{MST_STA11TO_MN}))^{**2}]$$

$$\text{MST_STA16STRS_V} = \text{SQRT}[(0.2634 * (\text{NFBAL} - \text{NFBAL_MN}) + 0.3657 * \text{SQRT}((\text{MST_STA16PRPB} - \text{MST_STA16PRPB_MN})^{**2} + (\text{MST_STA16PLB} - \text{MST_STA16PLB_MN})^{**2}))^{**2} + 3 * (0.1829 * (\text{MST_STA11TO} - \text{MST_STA11TO_MN}))^{**2}]$$

Yoke Bending Parameters

REDY_STA12BB

Red yoke beam bending, station 12.75, coupled calibration, in-lb

$$= \text{REDY_STA12BB_M} - 0.562 * \text{REDINBDSPNDL_BS}$$

REDY_STA12CB

Red yoke chord bending, station 12.75, coupled calibration, in-lb
= REDY_STA12CB_M - 3.3588 * REDINBDSPNDL_CS

L SofDAS Safety of Flight Requirements

The TTR requires significant safety-of-flight (SOF) monitoring for testing in the National Full-Scale Aerodynamic Complex (NFAC). Monitoring of critical channels will be accomplished with the Safety of Flight Data Acquisition System (SofDAS), which allows the real-time display of measured loads and derived data. See Ref. 18 (van Aken, WN-06-013) for a general overview of NFAC methods. The following material is derived from Section I of the LRTA UH-60 Software Requirements Document (Ref. 12).

Summaries and justifications for the rotor and TTR safety-of-flight load limits can be found in the TTR Load Limit Summary (Willink, 2016, Ref. 19), TTR SOF Summary (Willink, 2018, Ref. 20), and Bell Reports 699-616-004 and 699-616-900 (Refs. 7 and 13).

The SofDAS system provides for simultaneous data acquisition of up to 96 analog signals at rates up to 2000 samples per second. In addition, the system can acquire digital data provided by the NFAC data system for storage and use in derived calculations. Selected SOF parameters are displayed on a monitor with updates at about 4 times/sec. Trim parameters displayed for the test director and rotor operator are also processed through the SofDAS system. SofDAS parameters are not stored in RDMS unless specifically required.

Computational Requirements

For both SOF and trim display, it is essential to minimize any time lag between data acquisition and display, and imperative to eliminate as many failure modes as possible. For these reasons, SofDAS does not synchronize with the shaft encoder. Based on experience, a display update rate near 4/sec is recommended.

For this test program, data will be acquired at 2000 samples/sec. Displayed values will include statistical values of both direct measurements as well as derived parameters. Some derived parameters are combinations of statistics while others require sample-by-sample calculations. The specific requirements are identified in this section.

The SofDAS system runs at a fixed, time-based sample rate with a fixed-size data buffer for statistical computations. It is not possible to use a 1/rev trigger to fill the data buffer with an exact integer number of rotor revolutions. Statistics for peak and vibratory (half peak-to-peak) loads are taken over a fixed-size buffer. Hence, the per/rev statistics are only approximate.

The buffer size for mean values is set with the SamplesForMean parameter (called "SamplesPerRev" in some older documents, meaning the number of samples *assumed* for one revolution). SamplesForMean can be changed during a run, but the statistics will be incorrect until at least one complete buffer has been filled with newly sampled data. The rotor is usually trimmed to tip Mach number, not rpm, so a fixed buffer size will rarely equal exactly an integer number of revs.

Based on the above considerations, the following requirements for buffer size apply:

- 1) All samples must be included.
- 2) The buffer size must be as close as possible to an integer number of revs.
- 3) The display update rate should be close to 4/sec.

The 699 rotor on the TTR operates at two nominal rotor speeds: 569 rpm in helicopter mode, and 478 rpm in airplane mode. Therefore, no single value of SamplesForMean will be adequate for the entire entry. 2000 s/sec at airplane mode rpm yields not quite 2 revs per buffer, and helicopter mode rpm yields somewhat more than 2 revs per buffer.

Two values are specified here, one for 569 rpm, thus 422 samples; and one for 478 rpm, hence 502 samples. The mean statistics should be calculated based on one of these two numbers of samples, determined by rotor rpm.

At 569 rpm and 2000 s/sec, 1 rev = 0.1054 sec = 211 samples. Hence 422 samples is just under 1/5 sec, which is acceptable for SOF monitoring. At 478 rpm, 1 rev = 0.1255 sec = 251 samples. Hence 502 samples is just under 1/4 sec, which is very close to the preferred value. In practice, 500 samples was used for the first TTR/699 entry.

Once computations are complete, the data are displayed on the SofDAS screen. The limits for each of the channels (measured and derived) are set to change the color of the display bars at 80% and 100% (yellow and red respectively) of the red line limits. The limits to be monitored on the Bar Chart display are provided at the end of this section.

SofDAS also serves as an incident recorder. Measured data to be stored can be found in the Instrumentation Requirements spreadsheet (“TTRInstrumentationRequirementsRevG”). The derived data included in this document will be available upon re-reduction of the raw stored data.

The parameters defined here closely parallel those in Section K, but are processed differently (not synchronized to 1/rev). They have the same names if they are defined identically. See Section K for a list of inputs.

Summaries and justifications for the rotor and TTR safety-of-flight load limits can be found in the References in Section A, notably the TTR Load Limit Summary (Willink 2016, Ref. 19), TTR Rotor SOF Summary (Willink 2018, Ref. 20), and Bell Reports 699-616-004 (Ref. 7) and 699-616-900 (Ref. 13). Another useful reference is the Instrumentation and Calibration Report, Bell Report 699-616-008 (Ref. 17).

Warning: Early versions of Bell Report 699-616-004 (Ref. 7) contain many typos, including SOF entries. Bell load limits were updated by NASA as appropriate for wind-tunnel operations; see in particular TCR042-TR40-092.

Balance Equations and Constants

The SofDAS system cannot use the balance calibration algorithms of Sections D through G. A much simpler but less accurate method is specified here. The reduction in accuracy is

small and acceptable for SOF monitoring. Balance SOF limits are determined by internal loads, so rotor loads referenced to the rotor hub center, in particular moments, are not always appropriate here. xxBAL parameters should not be confused with xx_BAL_Bn etc.

The following equations compute balance loads in a balance-centered axis system (Fig. 1). Shaft torque is computed separately. Sensitivity constants are given in Table 5. Due to issues with gauge NF180_B1, the voltage for NF180_B2 is substituted into the following equations.

$$\begin{aligned} \mathbf{AFBAL} &= \mathbf{KAF} * (\mathbf{AF000_B1} + \mathbf{AF090_B1} + \mathbf{AF180_B1} + \mathbf{AF270_B1}) \\ \mathbf{SFBAL} &= \mathbf{KSF} * (\mathbf{SF000_B1} + \mathbf{SF090_B1} + \mathbf{SF180_B1} + \mathbf{SF270_B1}) \\ \mathbf{NFBAL} &= \mathbf{KNF} * (\mathbf{NF000_B1} + \mathbf{NF090_B1} + \mathbf{NF180_B2} + \mathbf{NF270_B1}) \\ \mathbf{RMBAL} &= \mathbf{KRM} * (\mathbf{NF270_B1} - \mathbf{NF090_B1}) \\ \mathbf{PMBAL} &= \mathbf{KPM} * (\mathbf{NF180_B2} - \mathbf{NF000_B1}) \end{aligned}$$

Where

- AFBAL = axial force, lb
- SFBAL = side force, lb
- NFBAL = normal force, lb
- RMBAL = rolling moment, ft-lb
- PMBAL = pitching moment, ft-lb

AFnnn, SFnnn, and NFnnn denote Axial, Side, and Normal force strain gauges at azimuths 000, 090, 180, and 270. B1 denotes primary gauges. B2 denotes secondary gauges.

KRM and KPM are values from Table 2 of Ref. 21 (Meyn, 2016), multiplied by the balance radius = 12.74 in, converted to ft-lb/V.

AFBAL is approximately equivalent to AF_UNC_B1 etc.

Table 5. Rotor balance and torque tube load sensitivity constants (Ref. 21).
Values assume unity gain and must be divided by the actual gain used.

Constant	Description	Value	Units
KAF	Balance load sensitivity factor for axial force	271,971	lb/V
KSF	Balance load sensitivity factor for side force	283,625	lb/V
KNF	Balance load sensitivity factor for normal force	2,594,545	lb/V
KRM	Balance load sensitivity factor for roll moment	2,742,556	ft-lb/V
KPM	Balance load sensitivity factor for pitch moment	2,759,002	ft-lb/V
KTQ1	Torque tube sensitivity factor (primary)	-5192.88	ft-lb/V
KTQ2	Torque tube sensitivity factor (secondary)	-4994.65	ft-lb/V

Combined Balance Loads

For each data buffer, determine the mean values of AFBAL, SFBAL, PMBAL, and RMBAL:
AFBAL_MN, SFBAL_MN, PMBAL_MN, and RMBAL_MN

Separately compute the peak (_P) and vibratory (_V) net vibratory loads:

$$\mathbf{BAL_SHEAR_P} = \mathbf{SQRT(AFBAL^{**2} + SFBAL^{**2})}$$

$$\mathbf{BAL_MOM_P} = \mathbf{SQRT(PMBAL^{**2} + RMBAL^{**2})}$$

$$\mathbf{BAL_SHEAR_V} = \mathbf{SQRT[(AFBAL - AFBAL_MN)^{**2} + (SFBAL - SFBAL_MN)^{**2}]}$$

$$\mathbf{BAL_MOM_V} = \mathbf{SQRT[(PMBAL - PMBAL_MN)^{**2} + (RMBAL - RMBAL_MN)^{**2}]}$$

The outputs are time histories of the magnitudes for every sample in the buffer (always positive).

For each data buffer, compute and display the peak values of BAL_SHEAR_P, BAL_SHEAR_V, BAL_MOM_P, and BAL_MOM_V

Note: BAL_SHEAR and BAL_MOM are intended only for SOF monitoring and are not stored in RDMS (but see Appendix N).

Torque Measurements

Torque is measured by strain gauges on both the rotor mast and on the torque tube, the first for loads monitoring and the second for rotor torque measurement. The torque tube data are also used to monitor model support limits, so both sets of torque data must be treated as SOF channels.

Strain gauge MST_STA11TO measures mast torque and is an input to other derived parameters described later in this section. MST_STA12TO_B1 and MST_STA12TO_B2 are available as backups.

The input data for the torque tube is FCTQ_B1 (mV); FCTQ_B2 is available as a backup. For SofDAS, use the following equations:

TQTT_B1

Torque measured by the torque tube (primary), ft-lb
= KTQ1 * FCTQ_B1

TQTT_B2

Torque measured by the torque tube (secondary), ft-lb
= KTQ2 * FCTQ_B2

The coefficients assume unity gain and must be divided by the actual gain used.

Note: TQTT_B1 and TQTT_B2 are approximately equivalent to FCTQ_EU_B3 and FCTQ_EU_B4 (Sections F and G). TQTT_Bn are intended only for real-time SOF monitoring and are not stored in RDMS (but see Appendix N). For TQTT, the Bn suffixes refer to the strain gauge, not the calibration. For research data, use FCTQ_EU_Bn.

(The torque tube strain gauges are all named FCxx_Bn, meaning Flex Coupling, although torque is not actually measured at the coupling.)

Derived SOF Parameters for Bar Chart Monitoring

The parameters defined here closely parallel those in Section K, but are processed differently. In particular, the number of samples over which means, peak values, etc. are computed are different in Sections K and L. Parameters have the same names if they are defined identically to those in Section K, but are given extra suffixes here: “_SOF” for parameters to be displayed, and simply “S” for intermediate calculations not intended for storage or display.

Support Tube and Swashplate

Constant:

SamplesForMean

Number of samples to estimate mean values (approximately 2 rotor revolutions)
= 422 (helicopter rpm)
= 500 (airplane rpm)

As explained earlier, 502 samples would be more accurate for airplane rpm.

Support Tube Bending Moment, in-lb:

Several derived parameters require the vibratory support tube bending moment, SWTB_NETB_V, as a time history of the vibratory vector sum magnitude for every sample in the buffer.

For each data buffer, determine the mean values of SWTB_LATB and SWTB_FAB:

SWTB_LATB_MNS and SWTB_FAB_MNS

Compute and display the net vibratory bending moment:

$$\text{SWTB_NETB_VS} = \text{SQRT} [(\text{SWTB_LATB} - \text{SWTB_LATB_MNS})^{**2} + (\text{SWTB_FAB} - \text{SWTB_FAB_MNS})^{**2}]$$

The output, SWTB_NETB_VS, is a time history of the vibratory magnitude for every sample in the buffer (always positive).

Swashplate Anti-Drive Shear, lb:

Several derived parameters require the swashplate anti-drive shear, SWANTDR_SHEAR, as a time history of every sample in the data buffer. The measured data is calibrated for bi-directional slopes:

$$\begin{aligned} \text{SWANTDR_SHEAR_SOF} &= \text{SWANTDR_SHEAR_M} \text{ if } \text{SWANTDR_SHEAR_M} \text{ is } \geq 0 \\ &= 1.346 * \text{SWANTDR_SHEAR_M} \text{ if } \text{SWANTDR_SHEAR_M} \text{ is } < 0 \end{aligned}$$

The output, SWANTDR_SHEAR_SOF, is a time history for every sample in the buffer.

Compute and display the peak and half peak-to-peak values over one buffer.

For each data buffer, determine the mean value: SWANTDR_SHEAR_MNS

Swashplate Support Tube Derived Parameters

The following equations compute the vibratory stress magnitudes of the swashplate support tube, support tube plate, and support tube bolts. For each parameter, the maximum value over each buffer is equivalent to the nominal vibratory (half peak-to-peak) stress. The coefficients assume that SWTB_NETB_V has units of in-lb and SWANTDR_SHEAR has units of lb.

Support Tube Stress, psi:

$$\begin{aligned} \text{SWTB_STRESS_V_SOF} &= 0.45 * \text{SWTB_NETB_VS} \\ &+ 11.97 * \text{ABS}(\text{SWANTDR_SHEAR_SOF} - \text{SWANTDR_SHEAR_MNS}) \end{aligned}$$

Ref. Bell Report 699-616-004 Vol. I, Section 4.2.11 (Ref. 7) and Bell spreadsheet “Support Tube Plate and Bolts – Stress Equation”

Swashplate Tube Support Plate, psi:

$$\begin{aligned} \text{SWTB_SP_V_SOF} &= 0.49 * \text{SWTB_NETB_VS} \\ &+ 8.05 * \text{ABS}(\text{SWANTDR_SHEAR_SOF} - \text{SWANTDR_SHEAR_MNS}) \end{aligned}$$

Ref. Bell Report 699-616-004 Vol. I, Section 4.2.12 (Ref. 7) and Bell spreadsheet “Support Tube Plate and Bolts – Stress Equation”

Swashplate Tube Support Plate Bolts, psi:

Separate equations for shear (BOLT1) and tensile (BOLT2). (SWTB_BOLT1_V is always less than SWTB_BOLT2_V, but has a lower limit.)

$$\text{SWTB_BOLT1_V_SOF} = 0.061 * \text{SWTB_NETB_VS} \\ + 4.196 * \text{ABS}(\text{SWANTDR_SHEAR_SOF} - \text{SWANTDR_SHEAR_MNS})$$

$$\text{SWTB_BOLT2_V_SOF} = 0.65 * \text{SWTB_NETB_VS} \\ + 10.09 * \text{ABS}(\text{SWANTDR_SHEAR_SOF} - \text{SWANTDR_SHEAR_MNS})$$

Ref. Bell spreadsheet “Support Tube Plate and Bolts – Stress Equation.xlsx”

Swashplate Shear Derived Parameters

Swashplate shear load is a function of swashplate collective position. Collective position SPCOLL will change much more slowly than the buffer update rate, so the mean value provided via BDAS is adequate.

Constants

SP_OFFSET

Offset between zero actuator reference and swashplate support tube gauges, in
Determined during control console calibration. (See also COLLN.)

Need to separately compute the peak (_P) and vibratory (_V) swashplate shear:

$$\text{SPSHEAR_P_SOF} = \text{SQRT}(\text{SWTB_LATB}^{**2} + \text{SWTB_FAB}^{**2}) / (\text{SPCOLL} + \text{SP_OFFSET})$$

$$\text{SPSHEAR_V_SOF} = \text{SWTB_NETB_VS} / (\text{SPCOLL} + \text{SP_OFFSET})$$

The outputs, SPSHEAR_P and SPSHEAR_V, are time histories of the magnitudes for every sample in each data buffer.

For each data buffer, compute and display the peak values of SPSHEAR_P_SOF and SPSHEAR_V_SOF.

Swashplate Shear is used to monitor the Pin, Gimbal and Slider, Support Tube, and Support Plate (Bell Report 699-616-004 Vol. II, Section 3.3.14 ff, Ref. 7).

SPSHEAR_P_SOF is the same equation as SPSHEAR, but the real-time SOF data are processed differently and are not stored in RDMS.

Instrumentation Plate and Adapter

The hub accelerometers monitor both the instrumentation plate and the plate adapter. The plate has the lower limit. The acceleration limit depends on the weight of the instrumentation hat. Note: accelerometer axes are local to the mounting block, and not in balance axes.

For each data buffer, determine the mean values of HB_ACCELX and HB_ACCELZ:
HB_ACCELX_MNS and HB_ACCELZ_MNS

Compute the net vibratory hub acceleration:

$$\text{HUB_ACCEL_V_SOF} = \text{SQRT} [(\text{HB_ACCELX} - \text{HB_ACCELX_MNS})^{**2} + \text{HB_ACCELZ} - \text{HB_ACCELZ_MNS})^{**2}]$$

Compute and display the peak value for each buffer.

Ref. Bell Report 699-616-004 Vol. II, Section 3.3.39.4 & 3.3.40.4 (Ref. 7)

Proprotor Mast Derived Parameters for Monitoring

Mast stress limits, psi:

For each data buffer, determine the mean values of NFBAL, MST_STA11PRPB, MST_STA11PLB, MST_STA11TO, MST_STA16PRPB, and MST_STA16PL:

$$\text{NFBAL_MNS, MST_STA11PRPB_MNS, MST_STA11PLB_MNS, MST_STA11TO_MNS, MST_STA16PRPB_MNS, MST_STA16PLB_MNS}$$

Mast Sta 11.25 Stress, psi:

$$\text{MST_STA11STRS_P_SOF} = \text{SQRT} [(0.2887 * \text{NFBAL} + 0.4024 * \text{SQRT}(\text{MST_STA11PRPB}^{**2} + \text{MST_STA11PLB}^{**2}))^{**2} + 3 * (0.2012 * \text{MST_STA11TO})^{**2}]$$

$$\text{MST_STA11STRS_V_SOF} = \text{SQRT} [(0.2887 * (\text{NFBAL} - \text{NFBAL_MNS}) + 0.4024 * \text{SQRT}((\text{MST_STA11PRPB} - \text{MST_STA11PRPB_MNS})^{**2} + (\text{MST_STA11PLB} - \text{MST_STA11PLB_MNS})^{**2}))^{**2} + 3 * (0.2012 * (\text{MST_STA11TO} - \text{MST_STA11TO_MNS}))^{**2}]$$

Mast Sta 16.85 Stress, psi:

$$\text{MST_STA16STRS_P_SOF} = \text{SQRT} [(0.2634 * \text{NFBAL} + 0.3657 * \text{SQRT}(\text{MST_STA16PRPB}^{**2} + \text{MST_STA16PLB}^{**2}))^{**2} + 3 * (0.1829 * \text{MST_STA11TO})^{**2}]$$

$$\begin{aligned} \text{MST_STA16STRS_V_SOF} = & \text{SQRT} [(0.2634 * (\text{NFBAL} - \text{NFBAL_MNS}) \\ & + 0.3657 * \text{SQRT}((\text{MST_STA16PRPB} - \text{MST_STA16PRPB_MNS})^{**2} \\ & + (\text{MST_STA16PLB} - \text{MST_STA16PLB_MNS})^{**2}))^{**2} \\ & + 3 * (0.1829 * (\text{MST_STA11TO} - \text{MST_STA11TO_MNS}))^{**2}] \end{aligned}$$

For each data buffer, compute and display the maximum values of MST_STA11STRS_P_SOF, MST_STA11STRS_V_SOF, MST_STA16STRS_P_SOF, and MST_STA16STRS_V_SOF.

MST_STA11STRS_P_SOF is the same equation as MST_STA11STRS, but the real-time SOF data are processed differently and are not stored in RDMS; similar for STA16.

Yoke Derived Parameters for Monitoring

Yoke Sta 12.75 Bending Load, in-lb:

The following two equations are calibration corrections, so it is not appropriate to subtract means from the vibratory components of the input parameters:

$$\begin{aligned} \text{REDY_STA12BB_SOF} &= \text{REDY_STA12BB_M} - 0.562 * \text{REDINBDSPNDL_BS} \\ \text{REDY_STA12CB_SOF} &= \text{REDY_STA12CB_M} - 3.3588 * \text{REDINBDSPNDL_CS} \end{aligned}$$

For each data buffer, compute and display the min, max, and half peak-to-peak values of REDY_STA12BB_SOF and REDY_STA12CB_SOF.

Rotating System Gimbal Angles from Hub Measurements

These equations calculate the hub gimbal angles from the rotating RVDT's attached to the hub linkages. See Section H for details.

Calibrated Hub Flapping, deg

HB_FLAP_RB_SOF

Hub flap angle, red blade

$$= 0.002303 * (\text{HB_FLAP_RB_M})^{**2} + 0.39797 * \text{HB_FLAP_RB_M} - 2.86945$$

HB_FLAP_GRNB_SOF

Hub flap angle, green blade

$$= 0.002303 * (\text{HB_FLAP_GRNB_M})^{**2} + 0.39797 * \text{HB_FLAP_GRNB_M} - 2.86945$$

For both hub flapping angles, compute and display the half peak-to-peak values over each data buffer.

Swashplate Temperatures

Swashplate temperatures are acquired by the LXI T/C scanner in °F. Convert values to °C to match Bell SOF units. Note that other temperatures are acquired in °C and require no conversion.

SWASHPLATE0AZ

Swashplate temperature at zero azimuth, °C
= (SWASHPLATE0AZ_M – 32) / 1.8

SWASHPLATE180AZ

Swashplate temperature at zero azimuth, °C
= (SWASHPLATE180AZ_M – 32) / 1.8

Bar Chart Monitor Red-Line Engineering Units

Real-time monitoring limits are given in Tables 6-A through 6-E. Tables 6-A and 6-B present the red-line load limits for the bar chart monitor display. At the 100% levels, the parameter bars will turn red. At 80% of these loads, the parameters will be displayed as yellow. It is desired that the bar chart display be set up to show data for at least 120% of the redline limit for each channel. The “100% min” and “100% max” values are peak loads, and the HPP values are oscillatory loads (half peak-to-peak).

The derived parameters in Tables 6-B and 6-D use the equations defined above. The “xxx_V_SOF” and “BAL_xxx_V” parameters already have the mean values subtracted and should be compared against the MAX statistics stored in RDMS (not HPP).

In Table 6-C, the RPM, temperature and angle limits do not follow the same 80/100/120% limit logic as the loads measurements. Detailed limits are given in the notes following the table.

A few channels, notably the pitch link loads, bearing temperatures, and blade pitch transducers, should have similar values at all locations. In principle, it would be acceptable to display only the load, temperature, or angle for the worst-case transducer, but all values are specified in the Tables.

Warning: Tables 6-A through 6-E are not definitive for all operating conditions. Always check the latest Test Change Requests (TCRs) for up-to-date limits.

Table 6-A. Rotor monitoring limits, measured loads

Monitored Parameter	Units	Tagname	100% min	100% max	HPP
Actuator A	lb	CTRL_ACT_A_AX	-2693	2693	1088
Actuator B	lb	CTRL_ACT_B_AX	-2693	2693	1088
Actuator C	lb	CTRL_ACT_C_AX	-2693	2693	1088
Drive Link	lb	REDDL_AX			
Inboard Spindle In-Plane Load	lb	REDINBDSPNDL_CS			
Inboard Spindle Out-of-Plane Load	lb	REDINBDSPNDL_BS			
Outboard Spindle In-Plane Load	lb	REDOTBDSPNDL_CS			
Outboard Spindle Out-of-Plane Load	lb	REDOTBDSPNDL_BS			
Pitch Link (green)	lb	GRNPTCHLK_AX	-2424	2424	1023
Pitch Link (red; backup)	lb	REDPTCHLK_AX	-2424	2424	1023
Pitch Link (white, backup)	lb	WHTPTCHLK_AX	-2424	2424	1023
Station 117 Beam Bending	in-lb	REDB_STA117BB			
Station 117 Chord Bending	in-lb	REDB_STA117CB			
Station 117 Torsion	in-lb	REDB_STA117TO			
Station 32 Beam Bending	in-lb	REDB_STA32BB			
Station 32 Chord Bending	in-lb	REDB_STA32CB			
Station 58 Beam Bending	in-lb	REDB_STA58BB			
Station 58 Chord Bending	in-lb	REDB_STA58CB			
Station 70 Beam Bending	in-lb	REDB_STA70BB			
Station 70 Chord Bending	in-lb	REDB_STA70CB			
Station 70 Torsion	in-lb	REDB_STA70TO			
Station 90 Beam Bending	in-lb	REDB_STA90BB			
Station 90 Chord Bending	in-lb	REDB_STA90CB			
Swashplate Driver	lb	SWDR_SHEAR	-684	684	288
Station 17.5 Beam Bending	in-lb	REDY_STA17BB			
Station 17.5 Chord Bending	in-lb	REDY_STA17CB			

Refs.:

Willink, G., TTR Rotor Load Limits and SOF Summary v1.1, Appendix F, Feb. 2018 (Ref. 20).

Norman, T., SOF Limit Changes for Hover v2, March 2018 (TCR042-TR40-092).

Table 6-B. Rotor monitoring limits, derived parameters

Monitored Parameter	Units	Tagname	100% min	100% max	HPP
Sta 11.25 Mast Stress Equation	psi	MST_STA11STRS_P_SOF			
Sta 11.25 Mast Stress Equation	psi	MST_STA11STRS_V_SOF			
Sta 16.85 Mast Stress Equation	psi	MST_STA16STRS_P_SOF			
Sta 16.85 Mast Stress Equation	psi	MST_STA16STRS_V_SOF			
Swashplate Stress	psi	SWTB_STRESS_V_SOF	–	22,823	–
Swashplate Tube Support Plate	psi	SWTB_SP_V_SOF	–	5664	–
S/P Tube Support Plate Bolt1	psi	SWTB_BOLT1_V_SOF		8428	
S/P Tube Support Plate Bolt2	psi	SWTB_BOLT2_V_SOF		10,693	
Hub Acceleration	g	HUB_ACCEL_V_SOF			
Swashplate Shear	lb	SPSHEAR_P_SOF	–	1748	–
Swashplate Shear	lb	SPSHEAR_V_SOF	–	850	–
Swashplate Anti-Drive (1)	lb	SWANTDR_SHEAR_SOF	–1048	1048	521
Station 12.75 Beam Bending	in-lb	REDY_STA12BB_SOF			
Station 12.75 Chord Bending	in-lb	REDY_STA12CB_SOF			

Note:

(1) This channel requires a bi-linear calibration.

Table 6-C. Rotor monitoring limits, other

Note: not traditional NFAC 100% & 80% limits

Monitored Parameter	Units	Tagname	Warning	Max	Comments
CF Bearing Temperature (1)	°C	CFBRNG_REDY_RTD_M			Steady
backup	°C	CFBRNG_REDY_RTD_180_M			Steady
Hub Spring Temperature (1)	°C	HBSPRG_TEMP_GRN_M			Steady
backup	°C	HBSPRG_TEMP_RED_M			Steady
backup	°C	HBSPRG_TEMP_WHT_M			Steady
Swashplate Temperature (2)	°C	SWASHPLATE0AZ	102	138	Steady
Swashplate Temperature (2)	°C	SWASHPLATE180AZ	102	138	Steady
Hub Flapping (3)	deg	HB_FLAP_RB_SOF			HPP
backup	deg	HB_FLAP_GRNB_SOF			HPP

Notes:

(1) See Bell Report 699-616-004 (Ref. 7).

(2) Not documented in Bell reports, defined and stored in °C to match Bell SOF limits.

Real-time displays are in °F, limits are 216 °F and 280 °F.

(3) See Bell Report 699-616-004 (Ref 7).

Table 6-D. Balance monitoring limits

Monitored Parameter	Units	Tagname	100% max	HPP
Normal Force	lb	NFBAL	15,000	10,000
Balance Shear, peak	lb	BAL_SHEAR_P	8250	
Balance Shear, vibratory	lb	BAL_SHEAR_V	5000	
Balance Moment, peak (1)	ft-lb	BAL_MOM_P	68,344	
Balance Moment, vibratory (1)	ft-lb	BAL_MOM_V	66,543	
Flex-coupling torque	ft-lb	TQTT_B1	22,338	13,300
Flex-coupling torque (backup)	ft-lb	TQTT_B2	22,338	13,300

Note:

- (1) Balance moment limits are determined by combining hub moment and hub shear limits:
 $BAL_MOM = \text{Hub Moment} + 7.3085 * \text{Hub Shear}$
 (Ref. 19, Appendix E).

Certain limits are normally monitored at the Control Console or other locations and are not part of SofDAS. They are listed in Table 6-E for reference.

Table 6-E. Other monitoring limits (not SofDAS)

Mon. Channel	Units	Tagname	Warning	Max	Comments
Blade Pitch Angle (red)	deg	RB_PITCH			(1)
Blade Pitch Angle (green, backup)	deg	GB_PITCH			(1)
Shaft Speed, helicopter mode	rpm	RPM	541	597	569 ± 5%
Shaft Speed, airplane mode	rpm	RPM	455	501	478 ± 5%
				100% Max	
Tunnel Q, Yaw=0	psf	Q		262	
Tunnel Q, Yaw≠0	psf	Q		75	

Note:

- (1) Bell proprietary; should hit swashplate kinematic limits (“potato”) first.

M Miscellaneous Measurements

A few measurements, notably microphones and strut strain gauges, all collected here. No real-time data displays are required for the struts. Processing for the microphones is defined in the Acoustics Instrumentation/Test Plan (Ref. 22).

Individual Strut Loads (Uncorrected)

The following parameters are in *strut* axes: with the “tail” strut pointing upstream and the two sponson struts aft, Port and Starboard are to the left and right looking upstream, +AF is downstream, and +SF is to the right looking upstream. The struts and their axis system rotate with the T-frame.

Input strain gauge data:

STBD_AF_B1
Starboard Strut Axial Force Primary, lb

STBD_AF_B2
Starboard Strut Axial Force Backup, lb

STBD_SF_B1
Starboard Strut Side Force Primary, lb

STBD_SF_B2
Starboard Strut Side Force Backup, lb

PORT_AF_B1
Port Strut Axial Force Primary, lb

PORT_AF_B2
Port Strut Axial Force Backup, lb

PORT_SF_B1
Port Strut Side Force Primary, lb

PORT_SF_B2
Port Strut Side Force Backup, lb

NOSE_AF_B1
Nose Strut Axial Force Primary, lb

NOSE_AF_B2
Nose Strut Axial Force Backup, lb

NOSE_SF_B1
Nose Strut Side Force Primary, lb

NOSE_SF_B2

Nose Strut Side Force Backup, lb

Individual Strut Loads (Corrected)

Apply corrections for sensitive axis offset. The following parameters are in *strut* axes (defined above).

Individual coefficients are defined to allow for full cross-axis corrections. There are two sets of strain gauges, hence two sets of coefficients in the form $C_m_B_n$, where m denotes the correction and n denotes the strain gauge set (#1 or #2). All units are in lb. Strut loads are calibrated at the centers of the monoball mounts.

C1-C4 apply to the STBD strut

C5-C8 apply to the PORT strut

C9-C12 apply to the NOSE strut

Correction Coefficients for Primary Gauges:

$$C1_B1 = 1.00012$$

$$C2_B1 = -0.01844$$

$$C3_B1 = 0.99991$$

$$C4_B1 = -0.01529$$

$$C5_B1 = 1.00030$$

$$C6_B1 = 0.00898$$

$$C7_B1 = 1.00011$$

$$C8_B1 = -0.00901$$

$$C9_B1 = 1.00009$$

$$C10_B1 = 0.03714$$

$$C11_B1 = 0.99992$$

$$C12_B1 = 0.03360$$

Correction Coefficients for Secondary Gauges:

$$C1_B2 = 1.00010$$

$$C2_B2 = -0.01789$$

$$C3_B2 = 0.99993$$

$$C4_B2 = -0.01576$$

$$C5_B2 = 1.00032$$

$$C6_B2 = 0.00931$$

$$C7_B2 = 1.00012$$

$$C8_B2 = -0.00918$$

$$C9_B2 = 1.00004$$

$$C10_B2 = 0.03574$$

$$C11_B2 = 0.99996$$

$$C12_B2 = 0.03354$$

Strut Forces Corrected for Interactions

STBD_AF_B1_C

Starboard Strut Axial Force Primary, corrected for installation, lb
= C1_B1 * STBD_AF_B1 – C2_B1 * STBD_SF_B1

STBD_SF_B1_C

Starboard Strut Side Force Primary, corrected for installation, lb
= C4_B1 * STBD_AF_B1 + C3_B1 * STBD_SF_B1

STBD_AF_B2_C

Starboard Strut Axial Force Backup, corrected for installation, lb
= C1_B2 * STBD_AF_B2 – C2_B2 * STBD_SF_B2

STBD_SF_B2_C

Starboard Strut Side Force Backup, corrected for installation, lb
= C4_B2 * STBD_AF_B2 + C3_B2 * STBD_SF_B2

PORT_AF_B1_C

Port Strut Axial Force Primary, corrected for installation, lb
= C5_B1 * PORT_AF_B1 – C6_B1 * PORT_SF_B1

PORT_SF_B1_C

Port Strut Side Force Primary, corrected for installation, lb
= C8_B1 * PORT_AF_B1 + C7_B1 * PORT_SF_B1

PORT_AF_B2_C

Port Strut Axial Force Backup, corrected for installation, lb
= C5_B2 * PORT_AF_B2 – C6_B2 * PORT_SF_B2

PORT_SF_B2_C

Port Strut Side Force Backup, corrected for installation, lb
= C8_B2 * PORT_AF_B2 + C7_B2 * PORT_SF_B2

NOSE_AF_B1_C

Nose Strut Axial Force Primary, corrected for installation, lb
= C9_B1 * NOSE_AF_B1 – C10_B1 * NOSE_SF_B1

NOSE_SF_B1_C

Nose Strut Side Force Primary, corrected for installation, lb
= C12_B1 * NOSE_AF_B1 + C11_B1 * NOSE_SF_B1

NOSE_AF_B2_C

Nose Strut Axial Force Backup, corrected for installation, lb
= C9_B2 * NOSE_AF_B2 – C10_B2 * NOSE_SF_B2

NOSE_SF_B2_C

Nose Strut Side Force Backup, corrected for installation, lb
= C12_B2 * NOSE_AF_B2 + C11_B2 * NOSE_SF_B2

Net Strut Loads

Compute net loads in TTR balance axes:

AF is perpendicular to rotor shaft, lb, + right
NF is parallel to rotor shaft, lb, + forward
PM is pitching moment, parallel to T-frame yaw, ft-lb, + nose right
RM is rolling moment, perpendicular to T-frame yaw, ft-lb, + nose up

Assume inputs are corrected for 7.5-deg offsets.

Vertical loads are not calculated because there are no vertical strut load measurements. Rolling and pitching moments are incremental (“delta”) values that do not include TTR weight and assume no aerodynamic lift loads.

Constants

STRUT_NXOFF = 6.250	Nose strut longitudinal offset from balance center, ft
STRUT_PXOFF = 17.75	Port strut longitudinal offset from balance center, ft
STRUT_PYOFF = -4.083	Port strut lateral offset from centerline, ft
STRUT_SYOFF = 4.083	Starboard strut lateral offset from centerline, ft
STRUT_ZOFF = 3.073	Strut vertical offset from balance center (same for all), ft

Port and starboard longitudinal offsets are identical (so there is no “SXOFF”). Nose strut lateral offset is zero. Values are from Bell dwg 699-616-005 and should be verified during installation.

STRUT_AF_B1

Total strut axial force (primary), lb
= STBD_SF_B1_C + PORT_SF_B1_C + NOSE_SF_B1_C

STRUT_AF_B2

Total strut axial force (backup), lb
= STBD_SF_B2_C + PORT_SF_B2_C + NOSE_SF_B2_C

STRUT_NF_B1

Total strut normal force (primary), lb
= -STBD_AF_B1_C - PORT_AF_B1_C - NOSE_AF_B1_C

STRUT_NF_B2

Total strut normal force (backup), lb
= -STBD_AF_B2_C - PORT_AF_B2_C - NOSE_AF_B2_C

STRUT_PM_B1

Total strut pitching moment (primary), ft-lb
= - NOSE_SF_B1_C * STRUT_NXOFF
- (STBD_SF_B1_C + PORT_SF_B1_C) * STRUT_PXOFF
+ STBD_AF_B1_C * STRUT_SYOFF + PORT_AF_B1_C * STRUT_PYOFF

STRUT_PM_B2

Total strut pitching moment (backup), ft-lb
= - NOSE_SF_B2_C * STRUT_NXOFF
- (STBD_SF_B2_C + PORT_SF_B2_C) * STRUT_PXOFF
+ STBD_AF_B2_C * STRUT_SYOFF + PORT_AF_B2_C * STRUT_PYOFF

STRUT_YM_B1

Strut yawing moment (primary), ft-lb
= STRUT_AF_B1 * STRUT_ZOFF

STRUT_YM_B2

Strut yawing moment (backup), ft-lb
= STRUT_AF_B2 * STRUT_ZOFF

STRUT_RM_B1

Strut rolling moment (primary), ft-lb
= - STRUT_NF_B1 * STRUT_ZOFF

STRUT_RM_B2

Strut rolling moment (backup), ft-lb
= - STRUT_NF_B2 * STRUT_ZOFF

Acoustics Measurements (Ref. 22)**MIC1**

Free Field microphone #1

MIC2

Free Field microphone #2

MIC3

Surface microphone #1

MIC4

Surface microphone #2

N References

Important supporting documents include Alex Sheikman’s spreadsheet of data channels, calibration coefficients, etc. (“TTRInstrumentationRequirementsRevG”); a similar spreadsheet of DCMS data channels (“DCMS ChannelsTTRAcceptance”); a further spreadsheet defining data polarities (“PolarityRevB”); Larry Meyn’s balance calibration reports; and Bell reports listed below. Drawing numbers are Bell TTR drawings. Possibly useful documents include the JVX report “V-22 Performance Test Phase II 40- by 80-Foot Wind Tunnel Software Requirements.”

NFAC Test Change Requests (TCRs) and Software Change Requests (SCRs) document the evolution of data processing requirements over the course of the wind-tunnel test. Data were occasionally reprocessed well after conclusion of the wind-tunnel entry. Researchers are urged to check for TCRs and SCRs that may be generated after the present document is published.

A few proprietary documents are listed here in anticipation of eventual public release.

1. Acree, C. W., Sheikman, A. L., and Norman, T. R., “Wind Tunnel Performance Tests of a Full-Scale Proprotor on the Tiltrotor Test Rig,” NASA/ TM–20210021871, Dec. 2021.
2. van Aken, J. M., and Yang, L., “Development of a new State-of-the-Art Data Acquisition System for the National Full-Scale Aerodynamics Complex Wind Tunnels,” AIAA-2009-1346, 47th AIAA Aerospace Sciences Meeting, Orlando, FL, January 2009.
3. Acree, C. W., “Tiltrotor Test Rig Wind-Tunnel Test Data Catalog,” NASA/TM–20240008170, December 2024.
4. Acree, C. W., Meyn, L., and Norman, T. R., “TTR 699 Checkout Test NFAC Software Requirements Document,” Version 2.15, June 2024.
5. Meyn, L., “Preliminary 40- by 80-Foot Wind Tunnel Test Section Conditions Reference,” 29 March 1999.
6. Heyson, H. H., “Wind-Tunnel Testing of VTOL and STOL Aircraft,” NASA TM 78750, July 1978.
7. “NASA Large Scale Proprotor Design and Analysis Report,” Bell Report 699-616-004 Vols. I and II, Revision E, 20 December 2020. *Vol. I is Bell proprietary.*
8. “NASA Large Scale Proprotor Hardware Documentation Report,” Bell Report 699-616-006, Vols, I and II, 7 September 2011. *Bell proprietary. Vol. II is ITAR controlled.*
9. “NASA Large Scale Proprotor Operations and Maintenance Manual,” Bell Report 699-616-007, Rev. A, 19 July 2012. *Bell proprietary.*
10. Meyn, L. A., “TTR Balance 1.0 Calibration,” July 2014.

11. van Aken, J. M., "NFAC naming convention for balance components and balance derived parameters," NFAC Report WN-06-005v2, Nov. 2006.
12. "LRTA UH-60 Airloads Test NFAC Software Requirements Document," v. 1.6, Oct. 2010.
13. "Tiltrotor Test Rig Design and Analysis Report," Bell Report 699-616-900, 1 August 2012.
14. Acree, C. W., "Tiltrotor Test Rig Aerodynamic Tares," NASA/TM-20210021870, December 2021.
15. van Aken, J. M., "Balance Data Reduction Equations," NFAC Report WN-99-021, Dec. 1999.
16. "Tiltrotor Test Rig Control Console Operations and Maintenance Manual," Bell Report 699-616-016, 17 July 2012. *Bell proprietary.*
17. "NASA Large Scale Proprotor Instrumentation and Calibration Report," Bell Report 699-616-008, Rev. A, 15 April 2016.
18. van Aken, J. M., "NFAC Equations and Naming Convention for Standard Safety of Flight Parameters," NFAC Report WN-06-013v4, June 2009.
19. Willink, G., "Tilt Rotor Test Rig (TTR) Load Limit Summary," 22 Nov. 2016.
20. Willink, G., "TTR Rotor Load Limits and SOF Summary v1.1," Revision 0.11, 5 February 2018.
21. Meyn, L., "Tiltrotor Test Rig Balance Gauge Sensitivities for NFAC Safety of Flight Monitoring," March 2016 .
22. Schatzman, N. L., "Tiltrotor Test Rig (TTR) Acoustic Instrumentation/Test Plan," Version 1.13, March 2017.

Appendix: Recommended Changes

Changes to Section C, Tunnel Atmosphere and Model Operating Computations

CONSTF, CONSTM, and CONSTP are described as “normalization constants,” but they depend upon RHO and OMR and are in fact variables. Use instead “normalization factors” NRMLF_F etc. or similar.

HUM_DPT_ANA and HUM_DPT_DIG would more logically be DPT_ANA and DPT_DIG, for consistency with DPT. Their units are all temperature, not relative humidity.

RDMS has provisions for selecting different sources for several parameters, e.g. ALPHA_MEAS and ALPHA_INP. The choice is determined by the NFAC “factor table,” which is not accessible to researchers. For each such parameter, the database should include a flag indicating what was actually used, e.g. ALPHA_SEL=n, where n=0,1, etc.

Changes to Section D, Rotor Balance Data Reduction

The use of the suffix _Bn to denote parameters associated with particular balance calibrations is traditional but ambiguous. “_Bn” may also be used to denote bending gauges, backup measurements, or other parameters. Use instead “_Cn” for “calibration n” for clarity.

Changes to Sections F and G, Balance Data Reduction, (B3) and (B4)

DALPHA_B3 and DALPHA_B4 should logically use RTD, not 57.3.

Changes to Section I, Hub Loads

The distinction between loads measured by shaft strain gauges and loads measured by the balance should be consistently reflected in parameter names. The _SH_ discriminator should immediately follow the load type:

The tagnames AF_UNC_SH_A etc. would more logically be AF_SH_UNC_A etc.

The tagnames AF_BD_SH_A etc. would more logically be AF_SH_BD_A etc.

Changes to Section J, Spinner Loads

The tagnames AF_BA_SP etc. would more logically be AF_BD_SPN etc. SP could be confused with “swashplate” where “spinner” is meant.

Additions to Section K, Derived Parameters from Rotor Measurements

Some SOF parameters are not currently stored in RDMS, but are recommended to be added for future tests.

Inputs

AF_CB_B3	Corrected Axial Force, lb, from Section F
SF_CB_B3	Corrected Side Force, lb, from Section F
PM_CB_B3	Corrected Pitching Moment, ft-lb, from Section F
RM_CB_B3	Corrected Rolling Moment, ft-lb, from Section F

Equivalent loads for the B4 balance are also recommended: AF_CB_B4, SF_CB_B4, PN_CB_B4, and RM_CB_B4.

Combined balance loads:

For each revolution, determine the mean values of AF_CB_B3, SF_CB_B3, PM_CB_B3, and RM_CB_B3:

AF_CB_B3_MN, SF_CB_B3_MN, PM_CB_B3_MN, and RM_CB_B3_MN

Separately compute the peak (_P) and vibratory (_V) net vibratory loads:

$$\text{BAL_SHEAR_B3_P} = \text{SQRT}(\text{AF_CB_B3}^{**2} + \text{SF_CB_B3}^{**2})$$

$$\text{BAL_MOM_B3_P} = \text{SQRT}(\text{PM_CB_B3}^{**2} + \text{RM_CB_B3}^{**2})$$

$$\text{BAL_SHEAR_B3_V} = \text{SQRT}[(\text{AF_CB_B3} - \text{AF_CB_B3_MN})^{**2} + (\text{SF_CB_B3} - \text{SF_CB_B3_MN})^{**2}]$$

$$\text{BAL_MOM_B3_V} = \text{SQRT}[(\text{PM_CB_B3} - \text{PM_CB_B3_MN})^{**2} + (\text{RM_CB_B3} - \text{RM_CB_B3_MN})^{**2}]$$

These loads are equivalent to BAL_SHEAR_P, BAL_MOM_P, BAL_SHEAR_V, and BAL_MOM_V (Section L), but should be more accurate.

Equivalent computations for BAL_SHEAR_B4_P, BAL_MOM_B4_P, BAL_SHEAR_B4_V, and BAL_MOM_B4_V are also recommended.

A critical assumption here is that non-linear interactions and Bias/Dbias corrections are appropriate for internal balance loads, relative to the balance center, on the grounds that such corrections account for imperfections in the balance and instrumentation. In contrast, flex-coupling corrections and torque interactions are assumed to arise external to the balance. Weight tares and spinner tares are physical loads that are components of SOF loads and should not be subtracted, nor should balance SOF loads be taken at the hub center. These tares are operational loads and are different from any bias loads that occur during calibration.

Additions to Section L, SofDAS Safety of Flight Requirements:

Store AFBAL, NFBAL, SFBAL, PMBAL, and RMBAL in RDMS.

If per/rev statistics are *not* provided by RDMS, then also store AFBAL_MN, NFBAL_MN, SFBAL_MN, PMBAL_MN, RMBAL_MN, BAL_SHEAR_P, BAL_SHEAR_V, BAL_MOM_P, and BAL_MOM_V. These per-buffer values are close approximations to per-rev values from Section K.