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Broadband Fan Noise Prediction System for Turbofan Engines

Volume 2: BFaNS User's Manual and Developer's Guide

Bruce L. Morin
Pratt & Whitney, East Hartford, Connecticut

November 2010

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Summary

Pratt & Whitney has developed a Broadband Fan Noise Prediction System (BFaNS) for turbofan engines. This system computes the noise generated by turbulence impinging on the leading edges of the fan and fan exit guide vane, and noise generated by boundary-layer turbulence passing over the fan trailing edge. BFaNS has been validated on three fan rigs that were tested during the NASA Advanced Subsonic Technology Program (AST). The predicted noise spectra agreed well with measured data. The predicted effects of fan speed, vane count, and vane sweep also agreed well with measurements.

The noise prediction system consists of two computer programs: Setup_BFaNS and BFaNS. Setup_BFaNS converts user-specified geometry and flow-field information into a BFaNS input file. From this input file, BFaNS computes the inlet and aft broadband sound power spectra generated by the fan and FEGV. The output file from BFaNS contains the inlet, aft and total sound power spectra from each noise source.

This report is the second volume of a three-volume set documenting the Broadband Fan Noise Prediction System:

Volume 1: Setup_BFaNS User's Manual and Developer's Guide
Volume 2: BFaNS User's Manual and Developer's Guide
Volume 3: Validation and Test Cases

The present volume begins with an overview of the Broadband Fan Noise Prediction System, followed by step-by-step instructions for installing and running BFaNS. It concludes with technical documentation of the BFaNS computer program.

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Broadband Fan Noise Prediction System for Turbofan Engines
Volume 2: BFaNS User's Manual and Developer's Guide

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1.0 Introduction

In early turbofan engines, the fan blade passage tone and higher harmonics dominated the fan noise level when compared to fan broadband noise. However, engine makers have been very successful at reducing fan tone noise by decreasing fan tip speed, providing ample spacing between airfoil rows, carefully selecting the airfoil counts, and acoustically treating the fan duct. In fact, tone noise reduction has been so great that fan broadband noise is now a major contributor to the overall engine noise level.

Under NASA funding, Pratt & Whitney has developed a Broadband Fan Noise Prediction System (BFaNS) for turbofan engines. This prediction system is built around acoustic theories developed by Hanson (Refs. 1 to 4) and Glegg (Refs. 5 to 7). These theories account for noise generated by turbulence impinging on the leading edges of the fan and fan exit guide vane (FEGV), and noise generated by boundary-layer turbulence passing over the fan trailing edge.

Figure 1 shows the fan broadband noise sources that can be calculated with BFaNS. The blade tip-noise and blade self-noise calculations are limited to subsonic blade-tip relative Mach numbers. There are no limitations on the other sources.

Figure 2 shows the organization of the Broadband Fan Noise Prediction System, which consists of two computer programs: Setup_BFaNS and BFaNS. Setup_BFaNS converts user-provided geometry and flow-field information into a BFaNS input file (bfans.input). From this input file, BFaNS computes the inlet and aft broadband sound power spectra generated by the fan and FEGV. The output file (bfans.output) contains the inlet, aft and total sound power spectra from each noise source shown in Figure 1, along with the combined sound power spectra from all sources. Both Setup_BFaNS and BFaNS use control files (also referred to as author files) that allow the user to modify the way the programs operate.

This report is the second volume of a three-volume set. The present volume begins with an overview of the noise-prediction methodology, followed by step-by-step instructions for installing and running BFaNS. It concludes with technical documentation of the BFaNS computer program. Volume 1 provides instructions for running Setup_BFaNS, and Volume 3 provides validation and test cases.

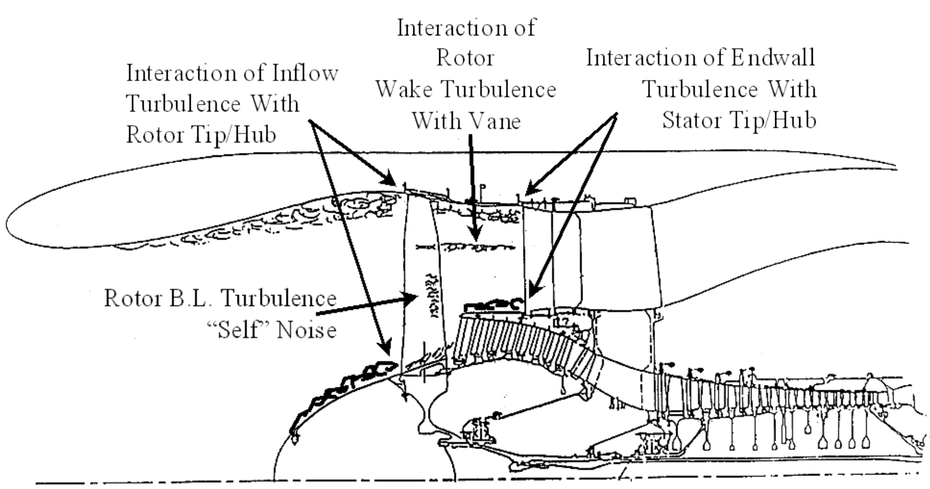

Figure 1.—Fan broadband noise sources predicted by BFaNS.

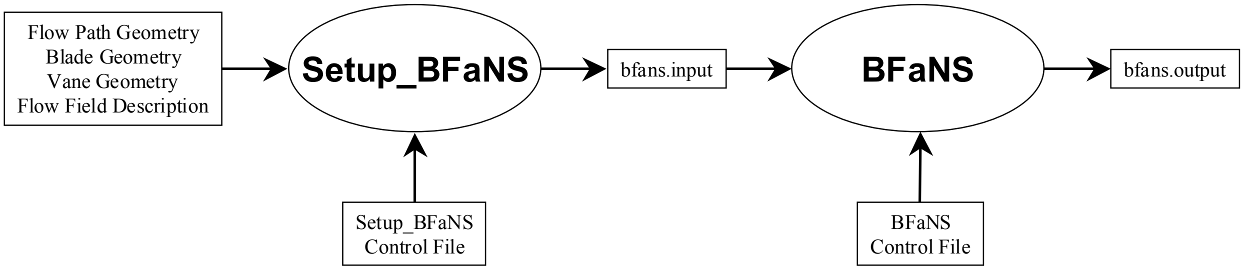

Figure 2.—Organization of BFaNS.

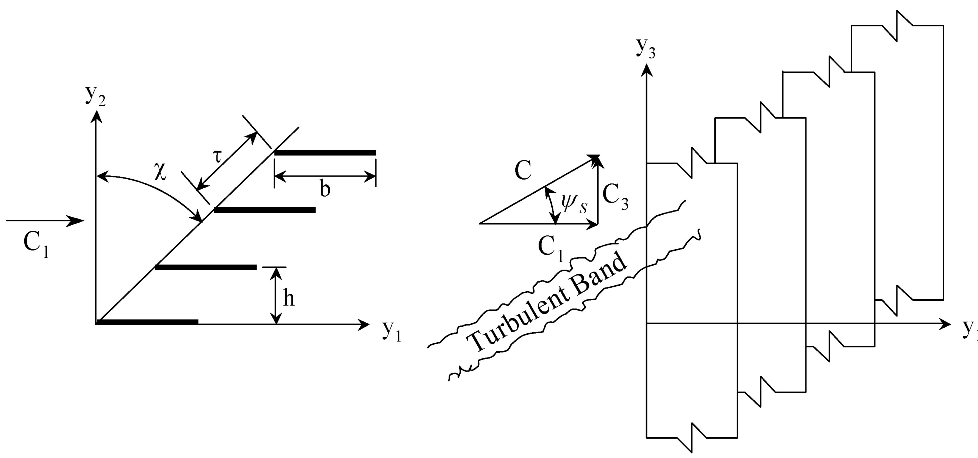

Figure 3.—Cascade studied by Hanson.

2.0 Noise-Prediction Methodology

Fan broadband noise can result from turbulence impinging on leading edges (turbulent inflow noise), and turbulence convecting past trailing edges (self noise). This section summarizes the methods used in BFANS to compute turbulent inflow noise and self noise. Papers and reports by Hanson (Refs. 1 to 4) and Glegg (Refs. 5 to 7) provide more detailed discussions of the theory.

2.1 Turbulent Inflow Noise

The interaction of turbulence with the rotor and stator leading edges can be a major source of broadband noise in turbofan engines. For this noise source, Hanson (Ref. 4) derived an expression that relates sound power to the inflow turbulence characteristics and cascade geometry. This was done by formally adapting Glegg's harmonic cascade theory (Ref. 8) to the random inflow problem. In later work, Hanson included the effects of blade row reflection and transmission (Refs. 9 and 10), though these effects have yet to be incorporated into BFaNS.

Using his theory, Hanson developed a computer program (BBCascade) that predicts the noise generated by a band of turbulence impinging on a cascade, as shown in Figure 3. The geometry consists of a rectilinear cascade of flat plates aligned with the mean flow direction (i.e., zero steady loading). The cascade span is assumed to be infinite. The mean flow is assumed to be uniform, and the boundaries far upstream and far downstream are assumed to be non-reflecting.

Within BFANS, BBCascade is applied to the rotor and stator in a stripwise manner. The inflows to the rotor and stator are divided into several turbulent bands. The bands are non-uniformly spaced, and are concentrated in regions of strong gradients in the turbulence profile. BFaNS computes the upstream and downstream sound power produced by the interaction of each turbulent band with the rotor or stator. The sound power from each band is then summed to yield the total upstream and downstream sound power.

2.2 Self Noise

Broadband noise is also generated when boundary-layer turbulence convects past the rotor and stator trailing edges. This source has been studied extensively for isolated airfoils and helicopter rotors, and Glegg recently extended these theories to trailing edge noise from semi-infinite cascades (Refs. 5 to 7). Glegg developed a computer program to predict fan self noise (but not FEGV self noise), and that program has been incorporated into BFaNS.

Glegg's approach relies on an experimental database of self noise from isolated NACA0012 airfoils (Ref. 11). This database is used to estimate the unsteady loading spectrum on the cascade for a given inlet Mach number, chord Reynolds number, and angle-of-attack. Given the unsteady loading spectrum, Glegg computes the noise that would be radiated by the cascade, including the scattering effect of the adjacent blades. The calculation is coupled to the radial modes of the annular duct (assuming uniform axial flow).

In Glegg's computer program, the rotor is divided into several uniformly spaced segments. The program computes the upstream and downstream sound power produced by each strip. The sound power from each strip is then summed to yield the total upstream and downstream sound power.

3.0 Installation and Execution of BFaNS

This section provides instructions for installing and running BFaNS. Refer to Section 4.0 for technical documentation of the computer program.

3.1 Installation

Appendix B provides instructions for installing the Broadband Fan Noise Prediction System (Setup_BFaNS and BFaNS) on Unix-based computers. Both computer programs are written in FORTRAN 77. Appendix C explains how to run the BFaNS test case.

3.2 Run Procedure

Table 1 shows the step-by-step process for running BFaNS. Sections 3.2.1 through 3.2.3 describe the details of each step.

TABLE 1.—RUN PROCEDURE FOR BFANS

Step 1	Create BFaNS input file
Step 2	Create BFaNS author file
Step 3	Execute BFaNS

3.2.1 Create BFaNS Input File

To generate a BFaNS input file, the user must follow the instructions in the Setup_BFaNS Users' Manual and Developer's Guide (Ref. 12).

3.2.2 Create BFaNS Author File

The author file allows the user to change default values that are hardcoded in BFaNS. BFaNS will search the working directory for a file named "bfans.author". If this file exists, BFaNS will use it to override the internal defaults for various options. Appendix D shows a sample BFaNS author file. The MATLAB (The MathWorks, Inc.) program "bf_author.m" creates an author-file template. This program is located in the BFaNS source code directory.

The author file has distinct blocks of input referred to as cards, with each card beginning on a new line. A negative card number indicates that the card is turned off. A positive card number indicates that a card is turned on. This feature allows the user to activate/deactivate various options in BFaNS. Each card has five input parameters (two integer, two real and one alphanumeric), which are provided at the end of the line. When a card is turned on, its input parameters are accessible to most subroutines within BFaNS.

Table 2 describes the various options in BFaNS. These options are also described in Section 4.0.

TABLE 2.—FORMAT OF BFANS AUTHOR FILE

Card	Description
5000	If turned on, this card specifies the file name of the BFaNS input file, and the user will not be prompted to enter the file name.
500 through 5048	Reserved for future use
5050	If turned on, this card over-rides the default model scale (i.e. model fan diameter divided by full-scale fan diameter). The default model scale is 1.000.
5052	If turned on, BFaNS will compute narrowband spectra. The default is to compute 1/3-octave spectra.
5054	If computing 1/3-octave spectra (see Card 5052), this card over-rides the default first 1/3-octave band (default is 17, i.e. 50 Hz).
5056	If computing 1/3-octave spectra (see Card 5052), this card over-rides the default last 1/3-octave band (default is 40, i.e. 10,000 Hz).
5058	If computing narrowband spectra (see Card 5052), this card over-rides the default number of frequencies (default is 100)
5060	If computing narrowband spectra (see Card 5052), this card over-rides the default first narrowband frequency (default is 100).
5062	If computing narrowband spectra (see Card 5052), this card over-rides the default last narrowband frequency (default is 10000).
5064	If computing narrowband spectra (see Card 5052), this card over-rides the default bandwidth. To automatically compute the bandwidth, enter 0.0. This automatic option will set the bandwidth equal to the frequency step. The default is to automatically calculate the bandwidth.
5066	If turned on, this card over-rides the default ambient density at the observer location (default is 0.0765 lbm/ft**3). Note: the ambient density at the observer is currently not used by BFaNS.
5068	If turned on, this card over-rides the default ambient speed of sound at the observer location (default is 1116 ft/sec). Note: the ambient speed of sound at the observer is currently not used by BFaNS.
5070	If turned on, BFaNS will not compute blade tip noise
5072	If turned on, BFaNS will not compute blade hub noise
5074	If turned on, BFaNS will not compute blade self noise
5076	If turned on, BFaNS will not compute vane tip noise
5078	If turned on, BFaNS will not compute vane hub noise
5080	If turned on, BFaNS **will** compute vane self noise
5082	If turned on, BFaNS will not compute vane-wake interaction noise
5084	If turned on, this card over-rides the default ratio between the transverse and longitudinal integral length scale in the blade inlet boundary layers (default is 1.0)
5086 through 5090	These cards are used to control the duct eigenvalue and eigenmode calculation for the self-noise calculation. Do not use these.
5092	If turned on, this card over-rides the default number of turbulent bands in the blade tip region, blade hub region, vane tip region and vane hub region (default value is 4)
5094	If turned on, this card over-rides the default number of turbulent bands in the vane-wake interaction region (default value is 8)
5096	If turned on, this card over-rides the default number of radial segments to use in the self-noise calculation (default value is 10)
5098	If turned on, this card over-rides the default number of turbulent sub-bands to use in the turbulent inflow calculation (default is 10)
5100 through 5108	These cards are used to control the duct eigenvalue and eigenmode calculation for the self-noise calculation. Do not use these.
5110	If turned on, this card over-rides the default the Mach-number limit for BBCascade (default is 0.93)
5112	If turned on, this card over-rides the default Mach-number limit for the self noise calculation (default is 0.97)
5114 through 5120	These cards are used to control the self-noise calculation. Do not use these.

TABLE 2.—FORMAT OF BFANS AUTHOR FILE

Card	Description
5122	If turned on, this card over-rides the default value of inf in the jsplit routine. The value entered is the number of terms in thousands (i.e. enter 2 for 2000 terms). Default is 2 (i.e. 2000 terms).
5124	If turned on, this card over-rides the default value of err in the jsplit routine. Default is 0.0005.
9999	Indicates end of author file.

3.2.3 Execute BFaNS

Table 3 shows the procedure for executing BFaNS.

TABLE 3.—EXECUTING BFANS

Step 1	Follow the instruction in Sections 3.2.1 through 3.2.2.
Step 2	Go to the working directory.
Step 3	Execute BFaNS using the alias bf.
Step 4	After execution is complete, confirm that the output file "bfans.output" has been created in the working directory.

4.0 Program Documentation

This section provides technical documentation for the BFaNS computer program, which is written in FORTRAN 77. Appendix F shows the subroutine hierarchy.

4.1 Units

Program inputs and outputs are in English units. Subroutine “read_input” reads the input file, and converts everything to SI units. The default name for the input file is “bfans.input”, but the user can change the name using Card 5000 in the author file. All internal calculations are done in SI units.

4.2 Restart File

As BFaNS executes, it writes to a restart file (bfans.restart) that allows the BFaNS session to be terminated and restarted at a later time. The restart file is especially valuable for long runs, which have a greater chance of being terminated due to network problems, power failures or other unexpected reasons.

Upon execution, BFaNS checks the working directory to see if the restart file exists. If it does, then BFaNS reads the restart file and continues the calculation where it left off. If the restart file does not exist, then BFaNS starts the calculation from scratch.

BFaNS deletes the restart file after the BFaNS output file has been created.

4.3 Model Scale

The model scale is defined as the ratio of the model fan diameter to the full-scale fan diameter. For example, to scale predictions for a 22 in. diameter fan rig to a 112 in. diameter engine, the model scale is (22/112) or 0.196. The model scale is specified in Card 5050 of the author file. When Card 5050 is turned off, BFaNS uses a model scale of one.

4.4 Frequency Range

By default, BFaNS will compute 1/3-octave spectra from 50 to 10 kHz. However, the user can change the frequency limits in the following manner:

- Turn off Card 5052 in the author file (or remove this card completely).

- Specify the first 1/3-octave band number in Card 5054 (see **Error! Reference source not found.** for standard 1/3-octave bands).
- Specify the last 1/3-octave band number in Card 5056 (see **Error! Reference source not found.** for standard 1/3-octave bands).

To compute narrowband spectra,

- Turn on Card 5052 in the author file.
- Specify the number of frequencies (n_{freq}) in Card 5058.
- Specify the first frequency ($f_{\min}$) in Hz in Card 5060.
- Specify the last frequency ($f_{\max}$) in Hz in Card 5062.
- Specify the bandwidth (BW) in Hz in Card 5064. If zero is entered, the bandwidth is automatically calculated via,

$$BW = \frac{f_{\max} - f_{\min}}{n_{freq} - 1}$$

The frequency information provided by Cards 5052, 5054, 5056, 5058, 5060, 5062 and 5064 must correspond to the desired frequencies for the full-scale engine. The model-scale frequencies are determined via,

$$f_{model} = \frac{f_{engine}}{Model\ Scale}$$

TABLE 4.—ANSI STANDARD ONE-THIRD OCTAVE BANDS (REFS. 13 AND 14)

Band number	Center frequency (Hz)	Bandwidth (Hz)	Band number	Center frequency (Hz)	Bandwidth (Hz)
1	1.25	0.292	25	315	73.2
2	1.6	0.367	26	400	92.2
3	2	0.462	27	500	116
4	2.5	0.582	28	630	146
5	3.15	0.732	29	800	184
6	4	0.922	30	1000	232
7	5	1.16	31	1250	292
8	6.3	1.46	32	1600	367
9	8	1.84	33	2000	462
10	10	2.32	34	2500	582
11	12.5	2.92	35	3150	732
12	16	3.67	36	4000	922
13	20	4.62	37	5000	1161
14	25	5.82	38	6300	1461
15	31.5	7.32	39	8000	1839
16	40	9.22	40	10000	2316
17	50	11.6	41	12500	2915
18	63	14.6	42	16000	3670
19	80	18.4	43	20000	4620
20	100	23.2	44	25000	5817
21	125	29.2	45	31500	7323
22	160	36.7	46	40000	9219
23	200	46.2	47	50000	11606
24	250	58.2	48	63000	14611

All calculations in BFaNS are done at the model-scale frequencies. At each frequency (f_{model}), BFaNS compute the power spectral density of the sound power. From the power spectral density, BFaNS then computes the power spectrum via,

$$PWL\big|_{model} = 10\log_{10}\left(PSD\big|_{model}\right) + 10\log_{10}\left(BW\big|_{model}\right)$$

The full-scale power spectra are then computed via,

$$PWL\big|_{engine} = PWL\big|_{model} - 20\log_{10}\left(Model\ Scale\right)$$

$$f_{engine} = f_{model}\left(Model\ Scale\right)$$

4.5 Turbulent Inflow Noise

BBCascade is applied to the rotor and stator in a stripwise manner. The inflows to the rotor and stator are divided into several turbulent bands. The bands are non-uniformly spaced, and are usually concentrated in regions of strong gradients in the turbulence profile (the distribution of bands can be set by the user – see below). BBCascade computes the upstream and downstream sound power produced by the interaction of each turbulent band with the rotor or stator. The sound power from each band is then summed to yield the total upstream and downstream sound power.

4.5.1 BBCascade

Hanson derived the following equation for the sound power generated by a band of turbulence interacting with a cascade (Ref. 4),

$$\frac{PWR^{\pm}}{PWR_{ref}} = constant \iint F^{\pm}(\overline{\alpha}, \overline{\upsilon}) \sum_{k} \phi_{22}\, d\overline{\alpha}\, d\overline{\upsilon}$$

where

$$constant = \frac{2\pi^2 BM_{stat}^2 \overline{\varpi}\Delta\overline{\varpi}}{\beta \overline{s}_e \left(M + Q_{12}M_T\right) Q_{33}} \left[\frac{1.4 Pr \Delta ra}{PWR_{ref}}\right]$$

This equation relates sound power to the cascade geometry, the mean flow field and the turbulence characteristics. The geometry consists of a rectilinear cascade of flat plates aligned with the mean flow direction (i.e., zero steady loading). The cascade span is assumed to be infinite. The mean flow is assumed to be uniform, and the boundaries far upstream and far downstream are assumed to be non-reflecting. Also, the turbulence characteristics are assumed to be constant over the band of turbulence. Using his theory, Hanson developed the BBCascade computer program to predict the noise due to turbulent inflow interacting with a rotor or stator cascade.

4.5.2 BBCascade Input

Appendix G shows an example of a BBCascade input file. For each turbulent band, BBCascade requires the following information about the cascade geometry and the flow field:

Cascade geometry.—Airfoil count, gap-to-chord ratio, lean angle, sweep angle, and average radius

Steady flow.—Mach number in the stationary frame, flow angle in the stationary frame, static pressure and speed of sound
Turbulence.—Integral length scale, turbulence intensity and radial span of turbulent band

Most of this information is available from the “bfans.input” file. However, the static pressure, stationary-frame Mach number and stationary-frame flow angle must be computed from the “bfans.input” file via,

$$P = \frac{\rho a^2}{\gamma} \quad \text{where} \quad \gamma = 1.4$$

$$M = \frac{\sqrt{C_z^2 + C_r^2 + C_\theta^2}}{a}$$

$$\tan\alpha = \frac{\sqrt{C_z^2 + C_r^2}}{C_\theta}$$

For the radially dependent quantities, BFaNS computes a spanwise average over each turbulent band via,

$$Q_{avg} = \frac{1}{r_{hi} - r_{lo}} \int_{r_{lo}}^{r_{hi}} Q dr$$

The Q variable can represent gap-to-chord ratio, lean angle, sweep angle, Mach number, flow angle, static pressure, speed of sound, integral scale or turbulence intensity, and (r_{lo}, r_{hi}) indicate the edges of the turbulent strip. The average radius and average airfoil rotational Mach number are defined as,

$$r_{avg} = \frac{r_{lo} + r_{hi}}{2}$$

$$M_{T,avg} = \frac{\Omega r_{avg}}{a_{avg}}$$

For the stator, the rotational speed (Ω) is zero.

4.5.3 BBCascade Modifications

Calculating the cascade response ($F^{\pm}$) is computationally intensive because it includes a slowly converging infinite product. To minimize the number of times that $F^{\pm}$ is calculated, BBCascade was modified to compute,

$$\frac{PWR}{PWR_{ref}} = constant \iint F^{\pm}(\overline{\alpha}, \overline{\upsilon}) \left\{ \int_{r_{lo}}^{r_{hi}} \sum_k \phi_{22} dr \right\} d\overline{\alpha} d\overline{\upsilon}$$

where

$$constant = \frac{2\pi^2 B M_{stat}^2 \overline{\varpi} \Delta\overline{\varpi}}{\beta \overline{s}_e (M + Q_{12} M_T) Q_{33}} \left[\frac{1.4 Pra}{PWR_{ref}} \right]$$

Note that the turbulence spectrum is now integrated over the span of the turbulent band, and the Δr term has been removed from the constant. In this manner, we only need to compute the cascade response once as long as the geometry and mean flow field are constant across the span of the cascade, even if the turbulence is non-uniform. If we were to use the original formulation of BBCascade on a non-uniform turbulence field, we would end up computing $F^{\pm}$ for every turbulent band, even if the cascade response were constant.

Appendix G compares the format of new BBCascade input file to that of the original BBCascade input file. Appendix H compares results from the new version of BBCascade to those from the original version for a stator cascade. Likewise, Appendix I compares results from the two versions of BBCascade for a rotor cascade. In general, agreement is very good between the two versions. The small differences are due to different steps being used in the wavenumber integration.

4.5.4 Mach-Number Limitation

Hanson's theory for turbulent inflow noise is not valid when the relative Mach number is sonic or greater. In addition, high subsonic Mach numbers cause numerical problems. Therefore, BFaNS will terminate the calculation when the relative Mach number exceeds 0.93 on any segment. The user can change this limit with Card 5110 in the author file.

4.5.5 Turbulence Spectrum

Hanson's theory formally accounts for anisotropic, non-homogeneous turbulence through the 3–D turbulent upwash spectrum. Unfortunately, this quantity is usually not available from measurements or computations. Consequently, we must rely on models that specify the 3–D upwash spectrum in terms of two readily available quantities, namely the intensity and length scale.

BBCascade has two options for the turbulence spectrum model:

(1) Isotropic turbulence via the Liepmann spectrum (Ref. 15), or
(2) Axisymmetric turbulence (Ref. 16)

BBCascade uses the Liepmann spectrum when the lateral and longitudinal intensities and length scales are equal. BBCascade uses the axisymmetric spectrum for all other cases.

The BFaNS input file only contains the longitudinal intensity and length scale. Therefore, the BFaNS default is to use the Liepmann spectrum. However, in Reference 4, Hanson showed the importance of anisotropy for noise generated by the inlet boundary interacting with the blade tip. Therefore, BFaNS has the option to set the ratio between the lateral and longitudinal length scales in the inlet boundary layer via Card 5084 in the author file.

4.5.6 Blade Tip Noise

By default, BFaNS will computes blade tip noise unless Card 5070 is turned on in the author file. The extent of the blade-tip region is determined by the boundary-layer thickness at the leading edge of the blade tip. By default, BFaNS divides the tip region into four equal bands. The user can change the number of bands using Card 5092 in the author file (warning—changing Card 5092 also changes the number of bands in the blade hub region, vane tip region and vane hub region).

4.5.7 Blade Hub Noise

By default, BFaNS will compute blade hub noise unless Card 5072 is turned on in the author file. The extent of the blade-hub region is determined by the boundary-layer thickness at the leading edge of the blade hub. By default, BFaNS divides the hub region into four equal bands. The user can change the number of bands using Card 5092 in the author file (warning—changing Card 5092 also changes the number of bands in the blade tip region, vane tip region and vane hub region).

4.5.8 Vane Tip Noise

By default, BFaNS will compute vane tip noise unless Card 5076 is turned on in the author file. The extent of the vane-tip region is determined by the boundary-layer thickness at the leading edge of the vane tip. By default, BFaNS divides the tip region into four equal bands. The user can change the number of bands using Card 5092 in the author file (warning—changing Card 5092 also changes the number of bands in the blade tip region, blade hub region and vane hub region).

4.5.9 Vane Hub Noise

By default, BFaNS will compute vane hub noise unless Card 5078 is turned on in the author file. The extent of the vane-hub region is determined by the boundary-layer thickness at the leading edge of the vane hub. By default, BFaNS divides the tip region into four equal bands. The user can change the number of bands using Card 5092 in the author file (warning—changing Card 5092 also changes the number of bands in the blade tip region, blade hub region and vane tip region).

4.5.10 Vane-Wake Interaction Noise

By default, BFaNS will compute vane-wake interaction noise unless Card 5082 is turned on in the author file. The extent of the vane-wake interaction region is determined by the boundary-layer thickness at the leading edge of the vane hub and vane tip. By default, BFaNS divides this region into eight equal bands. The user can change the number of bands using Card 5094 in the author file.

4.6 Self Noise

BFaNS uses a computer program that was developed by Glegg to predict fan self noise (but not FEGV self noise). Glegg's approach relies on an experimental database of self noise from isolated NACA0012 airfoils (Ref. 11). This database is used to estimate the unsteady loading spectrum on the cascade for a given inlet Mach number, chord Reynolds number, and angle-of-attack. Given the unsteady loading spectrum, Glegg computes the noise that would be radiated by the cascade, including the scattering effect of the adjacent blades. The calculation is coupled to the radial modes of the annular duct (assuming uniform axial flow).

In Glegg's computer program, the rotor is divided into several uniformly spaced segments. The program computes the upstream and downstream sound power produced by each strip. The sound power from each strip is then summed to yield the total upstream and downstream sound power.

4.6.1 Self-Noise Input

The original self-noise computer program requires the following information about the cascade geometry and the flow field:

> ***Cascade geometry***.—Blade count, tip radius, root radius and spanwise chord distribution
> ***Steady flow***.—Blade rotational speed, speed of sound, density, axial flow speed, and spanwise angle-of-attack distribution

The axial flow speed, speed of sound and density are assumed to be uniform. The blade is uniformly divided into several segments, the number of which is specified by the user. From this input, the program computes the following,

$$U = \Omega r$$

$$\beta = \tan^{-1}\left(\frac{C_z}{U}\right)$$

$$W = \sqrt{U^2 + C_x^2}$$

$$M = \frac{W}{a}$$

4.6.2 Self-Noise Modifications

Glegg's self-noise computer program was originally written in MATLAB. It was converted to a set of FORTRAN subroutines that are called within BFaNS. The FORTRAN code requires an input file that contains the following cascade and flow-field information:

Cascade geometry.—Blade count, tip radius, root radius, radii for each segment, and spanwise chord distribution
Steady flow.—Blade rotational speed, average speed of sound, average density, and spanwise distribution of: meridional flow speed, angle-of-attack, relative flow speed and relative flow angle

BFaNS creates this input file based on the information contained in "bfans.input". This new input format (see 0) eliminates the requirement for uniform axial flow speed (except when coupling to the duct modes, in which case the average axial flow speed is used). Note that the axial flow speed in the original file has been replaced with meridional flow speed to account for the non-zero component of radial velocity. Also, to account for swirl, the relative flow angle and relative flow speed are computed from,

$$\beta = \tan^{-1}\left(\frac{W_m}{W_\theta}\right)$$

$$W = \sqrt{W_m^2 + W_\theta^2}$$

This latter change allows the possibility of using the program to compute vane self noise (though it is not recommended).

For simplicity, the angle of attack is assumed to be uniform, and equal to the spanwise average angle of attack. However, the actual angle of attack distribution will be used when Card 5120 is turned on.

In addition to the above changes, the duct eigenvalue and eigenmode calculation was replaced with a faster method that was used by Glegg in some of his earlier work (Ref. 17). Appendix K compares results from the new version of the self-noise program to those from the original version. Agreement is very good between the two versions.

4.6.3 Mach-Number Limitation

Glegg's self-noise theory is not valid when the relative Mach number is sonic or greater. In addition, high subsonic Mach numbers cause numerical problems. Therefore, BFaNS will terminate the calculation when the relative Mach number exceeds 0.97 on any segment. The user can change this limit with Card 5112 in the author file.

4.6.4 Frequency Limitation

The self-noise prediction relies on an experimental database of self noise measured from isolated NACA0012 airfoils (Ref. 11). If the requested frequency exceeds the maximum frequency available in the database, BFaNS prints a warning to the screen, and enters zeroes in the output file.

4.6.5 Blade Self Noise

By default, BFaNS will compute blade self noise unless Card 5074 is turned on in the author file. Self noise is computed only for the portion of the blade span that is between the endwall boundary layers. By default, BFaNS divides this region into eight equal bands. The user can change the number of bands using Card 5096 in the author file (warning: changing Card 5096 also changes the number of segments in the vane self-noise calculation).

4.6.6 Vane Self Noise (Not Recommended)

By default, BFaNS *will not* compute vane self noise unless Card 5080 is turned on in the author file. Self noise is computed only for the portion of the vane span that is between the endwall boundary layers. By default, BFaNS divides this region into eight equal bands. The user can change the number of bands using Card 5096 in the author file (warning: changing Card 5096 also changes the number of segments in the blade self-noise calculation).

4.7 Output File

Appendix L shows a sample output file from BFaNS. The output file contains the upstream, downstream and total sound power spectra for each source, in addition to the spectra for all sources combined. The spectra apply to the full-scale engine (as determined by Card 5050 in the author file). Zeroes in the sound-power columns denote frequencies at which calculations were not performed (either by request, or due to program limitations). Although not shown in Appendix L, the end of the output file contains copies of the input and author files.

5.0 Concluding Remarks

Pratt & Whitney has developed a Broadband Fan Noise Prediction System (BFaNS) for turbofan engines. The noise prediction system consists of two computer programs: Setup_BFaNS and BFaNS. Setup_BFaNS converts user-specified geometry and flow-field information into a BFaNS input file. From this input file, BFaNS computes the inlet and aft broadband sound power spectra generated by the fan and FEGV. The output file from BFaNS contains the inlet, aft and total sound power spectra from each noise source.

The Broadband Fan Noise Prediction System has been documented in a three-volume report. The present volume provides detailed instructions and technical documentation for BFaNS. Volume 1 provides detailed instructions and technical documentation for Setup_BFaNS. Volume 3 provides validation and test cases for the prediction system.

Appendix A.—Symbols

A.1 Variables

a	speed of sound
B	airfoil count
BW	bandwidth
b	airfoil chord
$\vec{C}$	absolute velocity vector
$F^{\pm}$	upstream (-) and downstream (+) cascade response (see Ref. 4)
f	frequency
k	scattering index (see Ref. 4)
M	chordwise Mach number (see Ref. 4)
M_{stat}	stationary-frame Mach number (see Ref. 4)
M_T	airfoil rotational Mach number (see Ref. 4)
n_{freq}	number of frequencies
P	static pressure
PSD	power spectral density
$PWR^{\pm}$	upstream (-) and downstream (+) sound power (see Ref. 4)
PWR_{ref}	reference sound power (1×10^{-12} W)
Q_{ij}	transformation matrix from duct to cascade coordinates (see Ref. 4)
r	radius
s_e	see Reference 4
$\vec{U}$	blade velocity vector
$\vec{W}$	relative velocity vector
x	horizontal coordinate viewed from rear of engine
y	vertical coordinate viewed from rear of engine
z	axial coordinate

A.2 Greek Symbols

α	absolute flow angle; effective angle-of-attack
$\overline{\alpha}, \overline{\upsilon}$	lateral wavenumber components (see Ref. 4)
β	relative flow angle; $\sqrt{1-M^2}$ (see Ref. 4)
γ	specific-heat ratio
θ	tangential location
Λ	turbulent length scale
ρ	density
ϕ_{22}	upwash spectrum tensor
Ω	rotational speed of airfoil
ω	radian frequency

A.3 Subscripts

engine	engine scale
x	horizontal component
y	vertical component
z	axial component
r	radial component
θ	tangential component
m	meridional component
model	model scale
max	maximum
min	minimum
lo	lower edge of turbulent band
hi	upper edge of turbulent band

Appendix B.—Installing the BFaNS System

The BFaNS system can be downloaded from the following web site: http://www.grc.nasa.gov/WWW/5900/5940/code/BFANS/

B.1 Step Number I: Setting Up the Directory Structure

1. In your home directory, create a directory called **Codes**.
2. Copy the file **fans_nasa.tar** to your **~/Codes** directory.
3. In your **~/Codes** directory, extract the files using the following command:
   tar -xvf fans_nasa.tar
4. After executing this command, you will have a **~/Codes/fans_nasa** directory. This directory will contain the following sub-directories**:**
   setup_bfans: contains source code and make files for Setup_BFaNS
   bfans: contains source code and make files for BFaNS
   lib: contains source code and make files for GRAFIC (a freely distributed graphics library created by MIT)
   makeflags: contains compiler options for Sun, SGI, and IBM workstations
5. Appendix E lists the files contained in each directory

B.2 Step Number II: Setting Up the Graphics Library (GRAFIC)

1. Go to the **~/Codes/fans_nasa/lib** directory. There you will find libraries compiled for an SGI workstation (**libgrafic.a.Iris**), a Sun workstation (**libgrafic.a.Sun4**), and an IBM workstation (**libgrafic.a.Ibm6000**). You can use one of these existing libraries, or compile the library yourself. If you choose to use an existing library, proceed to step no. 2. If you choose to compile the library yourself, proceed to step no. 3.
2. If you are working on an SGI workstation (with iris architecture), type the command:
   cp libgrafic.a.Iris libgrafic.a
   If you are working on a Sun workstation (with svr4 architecture), type the command:
   cp libgrafic.a.Sun4 libgrafic.a
   If you are working on an IBM workstation (with rs6 architecture), type the command:
   cp libgrafic.a.Ibm6000 libgrafic.a
   For all the above workstations, proceed to Step no. III to compile Setup_BfaNS.
3. Go to the **~/Codes/fans_nasa/lib/grafic** directory.
4. If you are working on an SGI workstation (with iris architecture), type the command:
   make -f Makefile.Iris
   If you are working on a Sun workstation (with svr4 architecture), type the command:
   make -f Makefile.Sun4
   If you are working on an IBM workstation (with rs6 architecture), type the command:
   make -f Makefile.Ibm6000
   The above commands will create a file called **libgrafic.a** in your **~/Codes/fans_nasa/lib** directory. If you have problems compiling, go to the **~/Codes/fans_nasa/makeflags** directory and check the compiler options that are set for your workstation (i.e., **makeflags.Iris**, **makeflags.Sun4**, or **makeflags.Ibm6000**).

B.3 Step Number III: Compiling Setup_BFaNS

1. Go to the **~/Codes/fans_nasa/setup_bfans** directory.
2. If you are working on an SGI workstation (with iris architecture), type the command:
   make -f Makefile.Iris

If you are working on a Sun workstation (with svr4 architecture), type the command:

make -f Makefile.Sun4

If you are working on an IBM workstation (with rs6 architecture), type the command:

make -f Makefile.Ibm6000

The above commands will create an executable file called **setup_bfans.x** in your **~/Codes/fans_nasa/setup_bfans** directory. If you have problems compiling, go to the **~/Codes/fans_nasa/makeflags** directory and check the compiler options that are set for your workstation (i.e., **makeflags.Iris**, **makeflags.Sun4**, or **makeflags.Ibm6000**).

3. If you want to change the compiler optimization (or other options), edit the appropriate makeflags file and repeat step no. 2 in this section.

B.4 Step Number IV: Compiling BFaNS

1. Go to the **~/Codes/fans_nasa/bfans** directory.
2. If you are working on an SGI workstation (with iris architecture), type the command:

   make -f Makefile.Iris

   If you are working on a Sun workstation (with svr4 architecture), type the command:

   make -f Makefile.Sun4

   If you are working on an IBM workstation (with rs6 architecture), type the command:

   make -f Makefile.Ibm6000

   The above commands will create an executable file called **bfans.x** in your **~/Codes/fans_nasa/bfans** directory. If you have problems compiling, go to the **~/Codes/fans_nasa/makeflags** directory and check the compiler options that are set for your workstation (i.e., **makeflags.Iris**, **makeflags.Sun4**, or **makeflags.Ibm6000**).
3. If you want to change the compiler optimization (or other options), edit the appropriate makeflags file and repeat step no. 2 in this section.

B.5 Step Number V: Setting Up Aliases

1. Inside your **.cshrc** file, create the following aliases:

   alias sbf ~/Codes/fans_nasa/setup_bfans/setup_bfans.x
   alias bf ~/Codes/fans_nasa/bfans/bfans.x
2. In your home directory, type **source .cshrc**
3. These aliases are not required, but they make running much easier.

Appendix C.—Running the Test Case

The BFaNS test case can be downloaded from the following web site: http://www.grc.nasa.gov/WWW/5900/5940/code/BFANS/

C.1 Step Number I: Setting Up the Test Case

1. In your home directory, create a directory called **bbchallenge**.
2. Copy the file **bbchallenge.tar** to your **~/bbchallenge directory**.
3. In your **~/bbchallenge** directory, extract the files using the following command:

   tar -xvf bbchallenge.tar

   After executing this command, you will have the following 13 sub-directories inside ~/bbchallenge:

   bfans_geometry: contains files that describe the flow path, blade, and vane geometry
   bfans_cfd: contains files that describe viscous CFD-predicted flow field near blade l.e., blade t.e., vane l.e., and vane t.e. for each configuration and operating point
   bfans_data: not used (normally contains files that describe measured flow field near blade l.e., blade t.e., vane l.e., and vane t.e. for each configuration and operating point)
   bfans_sline: not used (normally contains files that describe inviscid streamline-predicted flow field near blade l.e., blade t.e., vane l.e., and vane t.e. for each configuration and operating point)
   54vr_spd1: contains test case for 54 radial vanes, sideline power
   54vr_spd2: contains test case for 54 radial vanes, cutback power
   54vr_spd3: contains test case for 54 radial vanes, approach power
   26vr_spd1: contains test case for 26 radial vanes, sideline power
   26vr_spd2: contains test case for 26 radial vanes, cutback power
   26vr_spd3: contains test case for 26 radial vanes, approach power
   26vs_spd1: contains test case for 26 radial vanes, sideline power
   26vs_spd2: contains test case for 26 radial vanes, cutback power
   26vs_spd3: contains test case for 26 radial vanes, approach power

C.2 Step Number II: Running a Test Case for Setup_BFaNS

1. Inside your ~**/bbchallenge/54vr_spd3** directory, type the command **sbf** or **~/Codes/fans_nasa/setup_bfans/setup_bfans.x**. This command will run Setup_BFaNS in the current directory.
2. When prompted for the name of the input file, enter **setupbfans.input**. This file contains the file names that describe the geometry and flow field (these files are located in the **bfans_geometry** and **bfans_cfd** sub-directories under **~/bbchallenge**), along with some additional information.
3. A figure will be displayed on the screen showing the blade velocity triangles. Look at the figure and confirm that the velocity triangles are correct relative to the blade orientation. Once satisfied, place your cursor inside this window, and type the letter **x** on your keyboard. Typing **x** will continue program execution.
4. A figure will be displayed on the screen showing the vane velocity triangles. Look at the figure and confirm that the velocity triangles are correct relative to the vane orientation. Once satisfied, place your cursor inside this window, and type the letter **x** on your keyboard. Typing **x** will continue program execution.
5. A figure will be displayed on the screen showing the fan-duct configuration. Look at the figure and confirm that the configuration is correct. Once satisfied, place your cursor inside this window, and type the letter **x** on your keyboard. Typing **x** will continue program execution.
6. A menu will be displayed to allow you to change the geometry. If you wish to change something, type in the number corresponding to your selection and press return. Then provide the requested

input. The old and new geometry will now be shown on the screen. Place your cursor inside the figure window, and type the letter **x** on your keyboard. Typing **x** will continue program execution, allowing you to make more changes to the geometry.

7. Type **99** to finish running Setup_BFANS.
8. You will now have a file named **bfans.input** in the **~/bbchallenge/54vr_spd3** directory. If you didn't make any changes to the geometry, then **bfans.input** should be nearly identical to **bfans.input.Sun4** which was created on a Sun workstation at P&W (there might be some very small differences depending on the compiler). To confirm that the two files are nearly identical, type the following command:
   diff bfans.input bfans.input.Sun4
   This command will show all differences between the two files.

C.3 Step Number III: Running a Test Case for BFaNS

1. Inside your **~/bbchallenge/54vr_spd3** directory, type the command **bf** or **~/Codes/fans_nasa/bfans/bfans.x**. This command will run BFaNS inside the current directory (note: to save time during code checkout, you might want to edit the **bfans.author** file to reduce the number of frequencies calculated).
2. When prompted for the name of the input file, enter **bfans.input**. This file contains the output from Setup_BFaNS.
3. When done, BFaNS will display "calculation completed" on the screen. You will now have a file named **bfans.output** in the **~/bbchallenge/54vr_spd3** directory. If you didn't make any changes to the geometry, then **bfans.output** should be nearly identical to **bfans.output.Sun4** which was created on a Sun workstation at P&W (there might be some very small differences depending on the compiler). To confirm that the two files are nearly identical, type the following command:
   diff bfans.output bfans.output.Sun4
   This command will show all differences between the two files.

Appendix D.—Sample BFaNS Author File

```
c-------------------------------------------------------------------------------
c author file for bfans
c-------------------------------------------------------------------------------
c section #1: read format is (a1,i5,a20,a54)
c-------------------------------------------------------------------------------
c card description      : a54
c-------------------------------------------------------------------------------
 -5000 input file name  : bfans.input
 -5002 through 5048     : reserved for future development
c-------------------------------------------------------------------------------
c section #2: read format is (a1,i5,a45,2i4,2f8,a5)
c-------------------------------------------------------------------------------
c card description                                 :  i4  i4      f8      f8   a5
c-------------------------------------------------------------------------------
 -5050 over-ride default model scale               :             1.0
    -1 (default = 1.0)                             :
 -5052 compute narrowband spectra                  :
 -5054 over-ride first 1/3 octave band             :  17
    -1 default = 17 (50 Hz)                        :
 -5056 over-ride last 1/3 octave band              :  40
    -1 default = 40 (10,000 Hz)                    :
 -5058 over-ride number of narrowband frequencies : 100
    -1 default = 100                               :
 -5060 over-ride first narrowband frequency (hz)  :           100.0
    -1 default = 100.0                             :
 -5062 over-ride last narrowband frequency (hz)   :         10000.0
    -1 default = 10000.                            :
 -5064 over-ride bandwidth (hz) for narrowband    :             0.0
    -1 default = 0.0 (i.e. autocalculate)          :
 -5066 over-ride ambient density (lbm/ft^3)       :          0.0765
    -1 default = 0.0765                            :
 -5068 over-ride ambient speed of sound (ft/s)    :           1116.
    -1 default = 1116.                             :
 -5070 do not compute blade tip noise              :
 -5072 do not compute blade hub noise              :
 -5074 do not compute blade self noise             :
 -5076 do not compute vane tip noise               :
 -5078 do not compute vane hub noise               :
 -5080 compute vane self noise                     :
 -5082 do not compute wake noise                   :
 -5084 over-ride inlet boundary layer anisotropy  :             1.0
    -1 rmoda = transverse/longitudinal             :
    -1 default = 1.0                               :
 -5086 over-ride approx. number of segments per   :   5
    -1 wavelength for computing radial mode shape :
    -1 default = 5                                 :
 -5088 over-ride minimum # of radial points       :  30
    -1 default = 30                                :
 -5090 over-ride maximum eigenvalue multiplier    :             1.1
    -1 default = 1.1                               :
 -5092 over-ride number of turbulent bands        :   4
    -1 to use in boundary layers                   :
    -1 default = 4                                 :
 -5094 over-ride number of turbulent band         :   8
    -1 to use between boundary layers              :
    -1 default = 8                                 :
 -5096 over-ride number of radial segments to use :  10
    -1 in self-noise calculation                   :
    -1 default = 10                                :
 -5098 over-ride number of turbulent sub-bands    :  10
    -1 in each turbulent band                      :
```

```
    -1 default = 10                                :
 -5100 over-ride eigenvalue tolerance              :            1d-11
    -1 default = 1d-11                             :
 -5102 over-ride eigenfunction tolerance           :            1d-06
    -1 default = 1d-6                              :
 -5104 over-ride tolerance on eigenvalue file      :            1d-06
    -1 default = 1d-6                              :
 -5106 over-ride 1st eigenvalue for mode 0,0       :            1d-10
    -1 default = 1d-10                             :
 -5108 over-ride initial step in eigenval solver   :              2.4
    -1 default = 2.4                               :
 -5110 over-ride maximum allowable mach number     :             0.93
    -1 in bbcascade                                :
    -1 default = 0.93                              :
 -5112 over-ride maximum allowable mach #          :             0.97
    -1 for self noise                              :
    -1 default = 0.97                              :
 -5114 do not use any cascade correction when      :
    -1 computing selfnoise                         :
 -5116 use approximate cascade correction when     :
    -1 computing selfnoise                         :
 -5118 use glegg routine for computing modes       :
 -5120 allow non-uniform a-o-a for selfnoise       :
 -5122 over-ride default inf in jsplit()           :  2
    -1 imoda = # terms (thousands)                 :
    -1 default = 2 (for 2000 terms)                :
 -5124 over-ride default err in jsplit()           :             5d-4
    -1 default = 5d-4                              :
 -5126 use fast version of jsplit()                :
    -1 might create overflow                       :
  9999 end of author file
```

Appendix E.—Directory Structure of ~/Codes/fans_nasa

~/Codes/fans_nasa/				
bfans/	lib/	lib/grafic/		setup_bfans/
Makefile.Ibm6000	libgrafic.a.Ibm6000	Apollo.m4	grflip.m4	Makefile.Ibm6000
Makefile.Iris	libgrafic.a.Iris	Athena.m4	grgrey.m4	Makefile.Iris
Makefile.Sun4	libgrafic.a.Sun4	Aviion.m4	grgri1.m4	Makefile.Sun4
Makefile.wnt		Dec.m4	grgrid.m4	add_points.F
angles.F	makeflags/	Hp9000.m4	grinit.m4	angles.F
author.def	makeflags.Ibm6000	Ibm6000.m4	grinpa.m4	arrowhead.F
bbcascade.F	makeflags.Iris	Iris.m4	grinpf.m4	author.def
bf_author.m	makeflags.Sun4	Makefile.Ibm6000	grinpi.m4	cal_coeff.F
bfans_ibm6000.F	makeflags.wnt	Makefile.Iris	grkey1.m4	calc_bl.F
bfans_iris.F		Makefile.Sun4	grkey2.m4	calc_rotor_wake.F
bfans_sun4.F		Newsys.m4	grkey3.m4	cascade.F
bfans_wnt.F		Stellar.m4	grkli1.m4	chan_duct_geom.F
capz.F		Sun4.m4	grklin.m4	circum_average.F
cascade2.F		Titan.m4	grklst.m4	constants.def
constants.def		Vapor.m4	grkpla.m4	converts.def
converts.def		Vax.m4	grlin1.m4	cross_ref.F
cross_ref.F		XApollo.c	grline.m4	debug_add_points.F
dateandtime.F		XAthena.c	grloc2.m4	debug_calc_bl.F
error.F		XAviion.c	grloct.m4	debug_calc_rotor_wake.F
exact_sol_hub.F		XDec.c	grmesg.m4	debug_estimate.F
f_ex.F		XHp9000.c	grmode.m4	debug_geom.F
f_ex2.F		XIbm6000.c	grmon2.m4	debug_get_bl.F
f_plus_minus2.F		XIris.c	grmon3.m4	debug_get_duct_geom.F
fbessj.F		XNewsys.c	grmov1.m4	debug_get_flow_data.F
fbessj0.F		XStellar.c	grmov2.m4	debug_get_geom.F
fbessj1.F		XSun4.c	grmov3.m4	debug_get_rotor_wake.F
fbessy.F		XTitan.c	grmovy.m4	debug_get_row_geom.F
fbessy0.F		XVapor.c	grnear.m4	debug_intersect.F
fbessy1.F		contng.m4	grper1.m4	debug_normalize.F
fgen.F		conxch.m4	grpers.m4	debug_scales.F
get_alpha_range.F		gr2alst.m4	grplst.m4	debug_stream_line.F
get_freqs.F		gr2axes.m4	grply2.m4	disp.F
get_input.F		gr2ctrl.m4	grply3.m4	error.F
get_nu_range.F		gr2curs.m4	grprnt.m4	estimate2.F
get_pratios_reba.F		gr2get.m4	grscal.m4	flow.F
getalphas.F		gr2lin1.m4	grscpt.m4	geom.F
getdeltas.F		gr2line.m4	grsfac.m4	get_bl.F
input_bb.F		gr2plst.m4	grsset.m4	get_duct_geom.F
input_new.F		gr2set.m4	grsymb.m4	get_file_name.F
interp.F		gr2sfac.m4	grthr1.m4	get_flow_data.F
jsp_te.F		gr2sset.m4	grthre.m4	get_geom.F
jsplit.F		grafic.doc	grtime.m4	get_mesh_data.F
lusolve.F		gralst.m4	grtran.m4	get_rho_sound.F
modes.F		granot.m4	grvalu.m4	get_rotor_wake.F
mysqrt.F		graxes.m4	grvec1.m4	get_row_geom.F
nasa_s.F		grcfil.m4	grvect.m4	get_velocity_data.F
parameters.def		grcler.m4	mrcon1.m4	interp.F
parameters.fgen.def		grclos.m4	mrcont.m4	intersect2.F
power_ratio.F		grcnew.inc		leasqr.F
read_author.F		grcntr.m4		ludcmq.F
read_input.F		grcol2.m4		mkdir_matlab.F
response.F		grcol3.m4		naca0012.F
run_bbcasc.F		grcolr.m4		normalize.F
s_pred.F		grcomn.inc		parabola.F
s_spec.F		grcon1.m4		parameters.def
trapezoid.F		grcon2.m4		plot_bl.m
turbspect.F		grcont.m4		plot_bv.F
zeros_ex_sub.F		grctrl.m4		plot_geom.F
		grcube.m4		plot_wake.m
		grcurs.m4		read_author.F
		grcutt.m4		reduce.m

~/Codes/fans_nasa/				
bfans/	lib/	lib/grafic/		setup_bfans/
		grdash.m4 grdrw2.m4 grdrw3.m4 grdump.m4 gredi1.m4 gredit.m4 greror.m4 grfil2.m4 grfil3.m4		save_get_bl.F sbf_author.m scales.F setupbfans.F solnq.F sort.F stream_function.F stream_line.F stress.F stress.m triangle.F upwash.F vect_comp.F wake_lean.F write_file.F

Appendix F.—BFaNS Subroutine Hierarchy

Bold items are called by multiple routines

- I. bfans
  - A. read_author
    - 1. cross_ref
  - B. read_input
    - **1. error**
  - **C. error**
  - D. run_bbcasc
    - **1. error**
    - **2. trapezoid**
      - **a. interp**
    - 3. bbcascade
      - a. input_bb
        - i. get_freqs
        - ii. angles
      - b. power_ratio
        - i. getdeltas
        - ii. get_nu_range
        - iii. get_pratios_reba
          - A) get_alpha_range
          - B) getalphas
          - C) f_plus_minus2
            - 1) cascade2
              - a) jsplit
              - b) lusolve
          - D) turbspect
  - E. fgen
  - F. modes
    - **1. error**
  - G. input
    - **1. error**
    - **2. trapezoid**
    - **3. interp**
  - H. s_pred
    - **1. error**
    - 2. get_input
      - **a. error**
    - 3. s_spec
    - 4. nasa_s
    - 5. response
      - **a. interp**
      - b. jsp_te
    - **6. interp**

Appendix G.—Modification to BBCascade Input File

Original Format

```
'bbcascade input file'                                     title
22          0.833E+00   0.239E+00   0.856E-02  -0.666E+00  b, gap/chord, machstat, thetastat, machtip
1           0.536E+01  -0.241E+00                          * angleconvention, lean (deg), sweep (deg)
0.641E-01   0.641E-01   0.832E-02   0.832E-02              intensity (long), intensity (lat), scale/r (long), scale/r (lat)
0.203E+04   0.112E+04   0.912E+00   0.787E-02              po, ao, r, delr
3                                                          ** spectrum type: 1 or 3 (1 for const BW, 3 for 1/3 OB)
0.250E+03   0.630E+05                                      ** see below for this line
0.          0.                                             *** deltaalf, deltanu

*   0 for cascade system, 1 for duct system
**  type = 1, const bw, input: f1 delfreq nfreq bw
**  type = 3, 1/3 ob, input: first freq, last freq (e.g. 63.  500.)
*** (deltaalf = 0. => default values)
```

Modified Format

```
'bbcascade input file'                      title
         22                                 b
          1                                 * angleconvention
  0.203E+04                                 po
          3                                 ** spectrum type: 1 or 3
  0.250E+03 0.630E+05                       ** see below for this line
         0.        0.                       *** deltaalf, deltanu

 *   0 for cascade system, 1 for duct system
 **  type = 1, const bw, input: f1 delfreq nfreq bw
 **  type = 3, 1/3 ob, input: first freq, last freq (e.g. 63.  500.)
 *** (deltaalf = 0. => default values)

        10 nsubseg
 0.829E+00  0.830E+00  0.831E+00  0.832E+00  0.833E+00  0.834E+00  0.835E+00  0.835E+00  0.836E+00  0.837E+00  gap/chord
 0.281E+00  0.277E+00  0.272E+00  0.265E+00  0.257E+00  0.248E+00  0.237E+00  0.224E+00  0.203E+00  0.125E+00  machstat
 0.332E-01  0.337E-01  0.340E-01  0.332E-01  0.319E-01  0.292E-01  0.244E-01  0.146E-01 -0.125E-01 -0.136E+00  thetastat
-0.663E+00 -0.664E+00 -0.664E+00 -0.665E+00 -0.666E+00 -0.666E+00 -0.667E+00 -0.668E+00 -0.669E+00 -0.671E+00  machtip
 0.523E+01  0.526E+01  0.529E+01  0.532E+01  0.535E+01  0.537E+01  0.539E+01  0.542E+01  0.545E+01  0.547E+01  lean (deg)
-0.623E+00 -0.541E+00 -0.457E+00 -0.367E+00 -0.275E+00 -0.184E+00 -0.966E-01 -0.158E-01  0.541E-01  0.941E-01  sweep (deg)
 0.295E-01  0.351E-01  0.407E-01  0.478E-01  0.552E-01  0.631E-01  0.719E-01  0.831E-01  0.103E+00  0.156E+00  intensity (long)
 0.295E-01  0.351E-01  0.407E-01  0.478E-01  0.552E-01  0.631E-01  0.719E-01  0.831E-01  0.103E+00  0.156E+00  intensity (lat)
 0.991E-02  0.985E-02  0.982E-02  0.986E-02  0.981E-02  0.945E-02  0.874E-02  0.763E-02  0.587E-02  0.229E-02  scale/r (long)
 0.991E-02  0.985E-02  0.982E-02  0.986E-02  0.981E-02  0.945E-02  0.874E-02  0.763E-02  0.587E-02  0.229E-02  scale/r (lat)
 0.908E+00  0.909E+00  0.910E+00  0.911E+00  0.912E+00  0.912E+00  0.913E+00  0.914E+00  0.915E+00  0.916E+00  r (ft)
 0.787E-03  0.787E-03  0.787E-03  0.787E-03  0.787E-03  0.787E-03  0.787E-03  0.787E-03  0.787E-03  0.787E-03  delr (ft)
 0.112E+04  0.112E+04  0.112E+04  0.112E+04  0.112E+04  0.112E+04  0.112E+04  0.112E+04  0.112E+04  0.112E+04  ao (ft/s)
```

Appendix H.—BBCascade Test Case - Stator

Original Input File

```
'Stator Case to Check BBCascade '
54         1.000      0.536      30.908     0.000  B, G, MachTotStat, Theta, MachTip
0          0.0        0.0                          Angle Convention, Lean, Sweep
0.01       0.01       0.01       0.01              Intens1, Intens2, Scale1, Scale2
2262.0     1127.2     0.917      0.458             Po, A0, R, DelR
1                                                  1 for const BW, 3 for 1/3 OB
1492.595   1492.595   30         100.0             see below *
1.0        1.0                                     DeltaAlf, DeltaNu
* For const BW, next line is first freq, freq step, Num freqs, BW
* For 1/3 OB  , next line is first freq, last freq
```

Original Output File

```
Stator Case to Check BBCascade
 Month/Day/Year: 7/ 9/2003, Time: 10:16:24
 Blade or Vane Count = 54, Gap/Chord = 1.000
 Input values for mean flow in stator frame:
      Mach Number = 0.536   Flow angle =  30.9
      Rotor rotational Mach number = 0.000
 Computed values:
      Relative Mach (rotor or stator) =  0.536,   Stagger =   30.9
  Angles (degrees)     Stagger Lean   Sweep
 In cascade system      30.9    0.0    0.0   - L&S input
 In  duct   system      30.9    0.0    0.0   - L&S computed
 Turbulence properties:
    I(axial)/W = 0.01000,   I(trans)/W = 0.01000
    L(axial)/R = 0.01000,   L(trans)/R = 0.01000
 Po=2262.0 lb/sq ft,   A0= 1127.2 ft/sec
 Fan Radius= 0.917 ft, Span of Turbulent Band= 0.458 ft
 DeltaAlf= 1.000, DeltaNu= 1.000
```

jfreq	freq	PWLup	PWLdn	Modified BBCascade freq	PWLup	PWLdn
1	1492.6	73.6	78.1	1492.6	73.9	78.3
2	2985.2	83.3	86.9	2985.2	83.3	86.9
3	4477.8	88.1	91.3	4477.8	88.0	91.2
4	5970.4	87.4	94.1	5970.4	87.4	94.1
5	7463.0	89.7	96.0	7463.0	89.6	96.1
6	8955.6	90.0	95.5	8955.6	89.9	95.6
7	10448.2	89.3	94.4	10448.2	89.2	94.5
8	11940.8	89.1	95.0	11940.8	89.0	95.0
9	13433.4	89.0	95.0	13433.4	88.9	95.0
10	14925.9	88.1	94.3	14925.9	88.0	94.4
11	16418.5	87.2	94.1	16418.5	87.1	94.2
12	17911.1	86.8	93.5	17911.1	86.7	93.5
13	19403.7	86.2	92.8	19403.7	86.1	92.8
14	20896.3	85.1	91.8	20896.3	85.0	91.8
15	22388.9	84.7	91.7	22388.9	84.6	91.7
16	23881.5	84.2	91.4	23881.5	84.2	91.4
17	25374.1	83.5	90.6	25374.1	83.4	90.6
18	26866.7	82.8	90.2	26866.7	82.7	90.3
19	28359.3	82.4	89.8	28359.3	82.4	89.9
20	29851.9	82.1	89.2	29851.9	82.0	89.2
21	31344.5	81.1	88.4	31344.5	81.1	88.4
22	32837.1	80.7	88.3	32837.1	80.7	88.3
23	34329.7	80.3	87.8	34329.7	80.3	87.9
24	35822.3	79.8	87.1	35822.3	79.7	87.2
25	37314.9	79.0	86.8	37314.9	79.0	86.8
26	38807.5	79.0	86.5	38807.5	79.0	86.5
27	40300.1	78.6	85.9	40300.1	78.5	85.9
28	41792.7	77.9	85.3	41792.7	77.8	85.3
29	43285.3	77.6	85.2	43285.3	77.5	85.2
30	44777.8	77.2	84.7	44777.8	77.1	84.8

Appendix I.—BBCascade Test Case—Rotor

Original Input File

```
'Rotor Case to Check BBCascade '
22          0.600       0.300       0.197       0.706   B, G, MachTotStat, Theta, MachTip
0           0.0         0.0                             Angle Convention, Lean, Sweep
0.01        0.01        0.01        0.01                Intens1, Intens2, Scale1, Scale2
1991.2      1105.9      0.917       0.458               Po, A0, R, DelR
1                                                       1 for const BW, 3 for 1/3 OB
1492.595    1492.595    30          100.0               see below *
1.0         1.0                                         DeltaAlf, DeltaNu
* For const BW, next line is first freq, freq step, Num freqs, BW
* For 1/3 OB  , next line is first freq, last freq
```

OriginalOutput File

```
Rotor Case to Check BBCascade
 Month/Day/Year: 7/ 9/2003, Time: 11: 0:35
 Blade or Vane Count = 22, Gap/Chord = 0.600
 Input values for mean flow in stator frame:
      Mach Number = 0.300   Flow angle =   0.2
      Rotor rotational Mach number = 0.706
 Computed values:
      Relative Mach (rotor or stator) =  0.766,   Stagger =  -66.9
  Angles (degrees)     Stagger Lean   Sweep
 In cascade system     -66.9    0.0    0.0   - L&S input
 In  duct   system     -66.9    0.0    0.0   - L&S computed
 Turbulence properties:
    I(axial)/W = 0.01000,   I(trans)/W = 0.01000
    L(axial)/R = 0.01000,   L(trans)/R = 0.01000
 Po=1991.2 lb/sq ft,   A0= 1105.9 ft/sec
 Fan Radius= 0.917 ft, Span of Turbulent Band= 0.458 ft
 DeltaAlf= 1.000, DeltaNu= 1.000
 BPF = 2981.2 Hz
```

jfreq	freq	PWLup	PWLdn
1	1492.6	76.7	73.5
2	2985.2	80.4	78.1
3	4477.8	83.5	83.7
4	5970.4	85.0	86.1
5	7463.0	85.9	88.1
6	8955.6	86.2	89.3
7	10448.2	86.2	89.9
8	11940.8	86.1	89.8
9	13433.4	85.9	89.2
10	14925.9	85.6	88.7
11	16418.5	85.3	88.6
12	17911.1	84.9	88.6
13	19403.7	84.6	88.5
14	20896.3	84.2	87.8
15	22388.9	83.8	87.3
16	23881.5	83.5	87.1
17	25374.1	83.1	87.1
18	26866.7	82.7	86.8
19	28359.3	82.3	86.2
20	29851.9	82.0	85.5
21	31344.5	81.6	85.3
22	32837.1	81.3	85.0
23	34329.7	81.0	84.7
24	35822.3	80.6	84.0
25	37314.9	80.3	83.7
26	38807.5	80.0	83.3
27	40300.1	79.7	83.2
28	41792.7	79.4	82.9
29	43285.3	79.0	82.5
30	44777.8	78.8	82.0

Modified BBCascade

freq	PWLup	PWLdn
1492.6	76.4	73.4
2985.2	80.3	78.2
4477.8	83.6	83.2
5970.4	85.1	86.0
7463.0	85.9	87.7
8955.6	86.0	89.7
10448.2	85.6	90.6
11940.8	86.2	89.6
13433.4	86.0	89.4
14925.9	85.6	89.0
16418.5	85.1	88.8
17911.1	84.8	88.8
19403.7	84.5	88.5
20896.3	84.1	87.9
22388.9	83.7	87.3
23881.5	83.4	87.3
25374.1	83.1	87.2
26866.7	82.7	86.9
28359.3	82.3	86.2
29851.9	82.0	85.6
31344.5	81.6	85.4
32837.1	81.3	85.2
34329.7	80.9	84.8
35822.3	80.6	84.3
37314.9	80.3	83.9
38807.5	80.0	83.5
40300.1	79.7	83.4
41792.7	79.3	83.0
43285.3	79.0	82.7
44777.8	78.7	82.2

Appendix J.—Sample Self-Noise Input File

```
sound power type (1=upstream, -1=downstream)    :       updown = -1
1 for if apprx. downstream blade response used  :      res_opt = 0
sound power reference level (watts)             :         wref = 1.E-12
ambient density (kg/m^3)                        :          roe = 1.184
ambient sound (m/s)                             :           co = 346.143
rotational speed (rad/s)                        :           om = 817.652
number of blades or vanes                       :            b = 22
number of radial segments                       :         nseg = 11
tip radius (m)                                  :            a = 0.279
hub radius (m)                                  :          hub = 0.084
radius (m) hub to tip                           :            r = 0.084
radius (m) hub to tip                           :            r = 0.103
radius (m) hub to tip                           :            r = 0.123
radius (m) hub to tip                           :            r = 0.142
radius (m) hub to tip                           :            r = 0.162
radius (m) hub to tip                           :            r = 0.182
radius (m) hub to tip                           :            r = 0.201
radius (m) hub to tip                           :            r = 0.221
radius (m) hub to tip                           :            r = 0.240
radius (m) hub to tip                           :            r = 0.260
radius (m) hub to tip                           :            r = 0.279
chord (m) hub to tip                            :            c = 0.075
chord (m) hub to tip                            :            c = 0.079
chord (m) hub to tip                            :            c = 0.083
chord (m) hub to tip                            :            c = 0.084
chord (m) hub to tip                            :            c = 0.086
chord (m) hub to tip                            :            c = 0.089
chord (m) hub to tip                            :            c = 0.092
chord (m) hub to tip                            :            c = 0.096
chord (m) hub to tip                            :            c = 0.097
chord (m) hub to tip                            :            c = 0.095
chord (m) hub to tip                            :            c = 0.095
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
angle of attack (deg) hub to tip                :          ang = 6.016
blade or vane angle (rad) hub to tip            :         beta = 0.988
blade or vane angle (rad) hub to tip            :         beta = 0.888
blade or vane angle (rad) hub to tip            :         beta = 0.802
blade or vane angle (rad) hub to tip            :         beta = 0.729
blade or vane angle (rad) hub to tip            :         beta = 0.665
blade or vane angle (rad) hub to tip            :         beta = 0.611
blade or vane angle (rad) hub to tip            :         beta = 0.564
blade or vane angle (rad) hub to tip            :         beta = 0.523
blade or vane angle (rad) hub to tip            :         beta = 0.487
blade or vane angle (rad) hub to tip            :         beta = 0.455
blade or vane angle (rad) hub to tip            :         beta = 0.427
meridional flow speed (m/s) hub to tip          :            u = 103.948
meridional flow speed (m/s) hub to tip          :            u = 103.948
meridional flow speed (m/s) hub to tip          :            u = 103.948
meridional flow speed (m/s) hub to tip          :            u = 103.948
meridional flow speed (m/s) hub to tip          :            u = 103.948
meridional flow speed (m/s) hub to tip          :            u = 103.948
meridional flow speed (m/s) hub to tip          :            u = 103.948
```

```
meridional flow speed (m/s) hub to tip        :          u = 103.948
meridional flow speed (m/s) hub to tip        :          u = 103.948
meridional flow speed (m/s) hub to tip        :          u = 103.948
meridional flow speed (m/s) hub to tip        :          u = 103.948
relative flow speed (m/s) hub to tip          :         ue = 124.522
relative flow speed (m/s) hub to tip          :         ue = 133.981
relative flow speed (m/s) hub to tip          :         ue = 144.590
relative flow speed (m/s) hub to tip          :         ue = 156.115
relative flow speed (m/s) hub to tip          :         ue = 168.367
relative flow speed (m/s) hub to tip          :         ue = 181.200
relative flow speed (m/s) hub to tip          :         ue = 194.498
relative flow speed (m/s) hub to tip          :         ue = 208.173
relative flow speed (m/s) hub to tip          :         ue = 222.154
relative flow speed (m/s) hub to tip          :         ue = 236.387
relative flow speed (m/s) hub to tip          :         ue = 250.830
integration step parameter                    :   nintstep = 0
turbulent boundary layer calculation          :       turb = 1
laminar boundary layer calculation            :        lam = 0
```

Appendix K.—Self-Noise Test Case

Input file for original FAU MATLAB code:

```
outfile='OUTPUT';                               %output file name
updown=-1;                                      %updown=1 for upstream sound power
                                                %updown=-1 for downstream sound power
fmin=1000;                                      %input minimum frequency
fmax=15000;                                     %input maximum frequency
N=15;                                           %input number of points in spectrum
dfreq=15.6;                                     %input freq. analysis bandwidth
%
U=93;                                           %input axial flow speed
a=0.2286;                               %input duct radius
hub=0.1;                                        %input hub radius
rpm=9120;Om=rpm*2*pi/60;                        %input rotor rpm
c=0.081+0*(1:10);                               %input blade chord(hub to tip)
ang=7+0*(1:10);                                 %input angle of attack(degrees)(hub to tip)
B=20;                                           %number of blades
Nintstep=5;                                     %integration step parameter
%
%%%%%%%%%%   OPTIONS    %%%%%%%%%%%
option=1;                               %option1=1 if NASA self noise code is to be used
                                                %option1=2 if default blade self noise spectra are to be used
                                                %option1=3 if data set in SLTdata.mat is to be used
                                                %
res_opt=0;                                      %res_opt=1 if approximate downstream blade response used

Turb=1;                                         % TBL calc.
Lam=0;                                          % LBL calc.

modeplot=1;                                     % Mode plot displayed if modeplot==1
jjmax=100;                                      % max number of modes to be displayed
%
plot_opt1=0;                                    % plot_option1=1 displays the wavenumbers, response
                                                %function and and source level for tip region
plot_opt2=0;                                    % plot_option2=1 displays the mode amplitudes vs duct
                                                %axial wavenumber

%
Nseg=length(c)                                  %number of points used to interpolate source level
if length(ang)~=Nseg;disp('ang and c must have same number of points');return;end


Wref=1e-12;                                     % sound power reference level
co=340;                                         % speed of sound
roe=1.2;                                        % density of air
%
```

	Comparison of MATLAB Versions (see note #1)			Comparison of FORTRAN and MATLAB Versions (see note #2,3)		
	FAU	P&W		P&W MATLAB	P&W FORTRAN	
Frequency	D.S. Sound Power	D.S. Sound Power	P&W - FAU	D.S. Sound Power	D.S. Sound Power	FORTRAN - MATLAB
(Hz)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)
1000	69.7423	69.7421	-0.0002	69.7418	69.7418	0.0000
2000	73.2749	73.2747	-0.0002	73.2744	73.2743	-0.0001
3000	76.2848	76.2848	0.0000	76.2847	76.2846	-0.0001
4000	81.4445	81.4445	0.0000	81.4445	81.4445	0.0000
5000	84.1604	84.1604	0.0000	84.1604	84.1604	0.0000
6000	85.0033	85.0033	0.0000	85.0033	85.0032	-0.0001
7000	84.5942	84.5942	0.0000	84.5942	84.5941	-0.0001
8000	83.1250	83.1248	-0.0002	83.1249	83.1248	-0.0001
9000	82.2663	82.2661	-0.0002	82.2661	82.2661	0.0000
10000	84.0167	84.0167	0.0000	84.0167	84.0166	-0.0001
11000	86.1071	86.1070	-0.0001	86.1070	86.1070	0.0000
12000	86.9741	86.9740	-0.0001	86.9739	86.9739	0.0000
13000	86.8632	86.8630	-0.0002	86.8630	86.8629	-0.0001
14000	86.0530	86.0528	-0.0002	86.0528	86.0528	0.0000
15000	84.5503	84.5499	-0.0004	84.5499	84.5499	0.0000

Notes:

1. in comparing MATLAB codes, both versions used MATLAB-generated eigenvalues
2. in comparing MATLAB to FORTRAN codes, both versions used FORTRAN-generated eigenvalues
3. the FORTRAN-generated eigenvalues are more accurate than the MATLAB-generated eigenvalues due to the eigenvalue solver used

Appendix L.—Sample BFaNS Output File

```
54-Vane Radial Stator
 Approach Condition (7,808 rpm

 blade tip noise (full scale)
     hz    up    dn   tot
 ----------------------------
   250.   0.0   0.0   0.0
   315.   0.0   0.0   0.0
   400.   0.0   0.0   0.0
   500.   0.0   0.0   0.0
   630.   0.0   0.0   0.0
   800.   0.0   0.0   0.0
  1000.   0.0   0.0   0.0
  1250.   0.0   0.0   0.0
  1600.   0.0   0.0   0.0
  2000.   0.0   0.0   0.0
  2500.   0.0   0.0   0.0
  3150.   0.0   0.0   0.0
  4000.   0.0   0.0   0.0
  5000.   0.0   0.0   0.0
  6300.   0.0   0.0   0.0
  8000.   0.0   0.0   0.0
 10000.   0.0   0.0   0.0
 12500.   0.0   0.0   0.0
 16000.   0.0   0.0   0.0
 20000.   0.0   0.0   0.0
 25000.   0.0   0.0   0.0
 31500.   0.0   0.0   0.0
 40000.   0.0   0.0   0.0
 50000.   0.0   0.0   0.0
 63000.   0.0   0.0   0.0

 blade hub noise (full scale)
     hz    up    dn   tot
 ----------------------------
   250.   0.0   0.0   0.0
   315.   0.0   0.0   0.0
   400.   0.0   0.0   0.0
   500.   0.0   0.0   0.0
   630.   0.0   0.0   0.0
   800.   0.0   0.0   0.0
  1000.   0.0   0.0   0.0
  1250.   0.0   0.0   0.0
  1600.   0.0   0.0   0.0
  2000.   0.0   0.0   0.0
  2500.   0.0   0.0   0.0
  3150.   0.0   0.0   0.0
  4000.   0.0   0.0   0.0
  5000.   0.0   0.0   0.0
  6300.   0.0   0.0   0.0
  8000.   0.0   0.0   0.0
 10000.   0.0   0.0   0.0
 12500.   0.0   0.0   0.0
 16000.   0.0   0.0   0.0
 20000.   0.0   0.0   0.0
 25000.   0.0   0.0   0.0
 31500.   0.0   0.0   0.0
 40000.   0.0   0.0   0.0
 50000.   0.0   0.0   0.0
 63000.   0.0   0.0   0.0
```

```
blade self noise (full scale)
    hz    up    dn   tot
----------------------------
  250.  66.8  58.8  67.4
  315.   0.0   0.0   0.0
  400.  75.9  68.6  76.6
  500.  75.9  71.8  77.3
  630.  80.1  76.5  81.7
  800.  83.6  80.4  85.3
 1000.  95.9  83.1  96.1
 1250.  86.2  86.2  89.2
 1600.  87.4  88.8  91.2
 2000.  90.1  90.0  93.1
 2500.  93.3  92.3  95.8
 3150.  96.5  96.8  99.7
 4000. 100.2 101.5 103.9
 5000. 101.9 103.9 106.0
 6300. 104.0 104.8 107.4
 8000. 104.9 104.1 107.6
10000. 104.8 109.1 110.5
12500. 105.2 109.8 111.1
16000. 104.7 108.6 110.1
20000. 103.6 107.5 109.0
25000.   0.0   0.0   0.0
31500.   0.0   0.0   0.0
40000.   0.0   0.0   0.0
50000.   0.0   0.0   0.0
63000.   0.0   0.0   0.0

vane tip noise (full scale)
    hz    up    dn   tot
---------------------------
  250.   0.0   0.0   0.0
  315.   0.0   0.0   0.0
  400.   0.0   0.0   0.0
  500.   0.0   0.0   0.0
  630.   0.0   0.0   0.0
  800.   0.0   0.0   0.0
 1000.   0.0   0.0   0.0
 1250.   0.0   0.0   0.0
 1600.   0.0   0.0   0.0
 2000.   0.0   0.0   0.0
 2500.   0.0   0.0   0.0
 3150.   0.0   0.0   0.0
 4000.   0.0   0.0   0.0
 5000.   0.0   0.0   0.0
 6300.   0.0   0.0   0.0
 8000.   0.0   0.0   0.0
10000.   0.0   0.0   0.0
12500.   0.0   0.0   0.0
16000.   0.0   0.0   0.0
20000.   0.0   0.0   0.0
25000.   0.0   0.0   0.0
31500.   0.0   0.0   0.0
40000.   0.0   0.0   0.0
50000.   0.0   0.0   0.0
63000.   0.0   0.0   0.0

vane hub noise (full scale)
    hz    up    dn   tot
---------------------------
  250.   0.0   0.0   0.0
  315.   0.0   0.0   0.0
```

```
  400.   0.0   0.0   0.0
  500.   0.0   0.0   0.0
  630.   0.0   0.0   0.0
  800.   0.0   0.0   0.0
 1000.   0.0   0.0   0.0
 1250.   0.0   0.0   0.0
 1600.   0.0   0.0   0.0
 2000.   0.0   0.0   0.0
 2500.   0.0   0.0   0.0
 3150.   0.0   0.0   0.0
 4000.   0.0   0.0   0.0
 5000.   0.0   0.0   0.0
 6300.   0.0   0.0   0.0
 8000.   0.0   0.0   0.0
10000.   0.0   0.0   0.0
12500.   0.0   0.0   0.0
16000.   0.0   0.0   0.0
20000.   0.0   0.0   0.0
25000.   0.0   0.0   0.0
31500.   0.0   0.0   0.0
40000.   0.0   0.0   0.0
50000.   0.0   0.0   0.0
63000.   0.0   0.0   0.0

vane self noise (full scale)
    hz    up    dn   tot
---------------------------
  250.   0.0   0.0   0.0
  315.   0.0   0.0   0.0
  400.   0.0   0.0   0.0
  500.   0.0   0.0   0.0
  630.   0.0   0.0   0.0
  800.   0.0   0.0   0.0
 1000.   0.0   0.0   0.0
 1250.   0.0   0.0   0.0
 1600.   0.0   0.0   0.0
 2000.   0.0   0.0   0.0
 2500.   0.0   0.0   0.0
 3150.   0.0   0.0   0.0
 4000.   0.0   0.0   0.0
 5000.   0.0   0.0   0.0
 6300.   0.0   0.0   0.0
 8000.   0.0   0.0   0.0
10000.   0.0   0.0   0.0
12500.   0.0   0.0   0.0
16000.   0.0   0.0   0.0
20000.   0.0   0.0   0.0
25000.   0.0   0.0   0.0
31500.   0.0   0.0   0.0
40000.   0.0   0.0   0.0
50000.   0.0   0.0   0.0
63000.   0.0   0.0   0.0

vane-wake interaction noise (full scale)
    hz    up    dn   tot
----------------------------------------
  250.   0.0   0.0   0.0
  315.   0.0   0.0   0.0
  400.   0.0   0.0   0.0
  500.   0.0   0.0   0.0
  630.   0.0   0.0   0.0
  800.   0.0   0.0   0.0
 1000.   0.0   0.0   0.0
```

1250.	0.0	0.0	0.0
1600.	0.0	0.0	0.0
2000.	0.0	0.0	0.0
2500.	0.0	0.0	0.0
3150.	0.0	0.0	0.0
4000.	0.0	0.0	0.0
5000.	0.0	0.0	0.0
6300.	0.0	0.0	0.0
8000.	0.0	0.0	0.0
10000.	0.0	0.0	0.0
12500.	0.0	0.0	0.0
16000.	0.0	0.0	0.0
20000.	0.0	0.0	0.0
25000.	0.0	0.0	0.0
31500.	0.0	0.0	0.0
40000.	0.0	0.0	0.0
50000.	0.0	0.0	0.0
63000.	0.0	0.0	0.0

total noise (full scale)

hz	up	dn	tot
250.	66.8	58.8	67.4
315.	0.0	0.0	0.0
400.	75.9	68.6	76.6
500.	75.9	71.8	77.3
630.	80.1	76.5	81.7
800.	83.6	80.4	85.3
1000.	95.9	83.1	96.1
1250.	86.2	86.2	89.2
1600.	87.4	88.8	91.2
2000.	90.1	90.0	93.1
2500.	93.3	92.3	95.8
3150.	96.5	96.8	99.7
4000.	100.2	101.5	103.9
5000.	101.9	103.9	106.0
6300.	104.0	104.8	107.4
8000.	104.9	104.1	107.6
10000.	104.8	109.1	110.5
12500.	105.2	109.8	111.1
16000.	104.7	108.6	110.1
20000.	103.6	107.5	109.0
25000.	0.0	0.0	0.0
31500.	0.0	0.0	0.0
40000.	0.0	0.0	0.0
50000.	0.0	0.0	0.0
63000.	0.0	0.0	0.0

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Pratt & Whitney has developed a Broadband Fan Noise Prediction System (BFaNS) for turbofan engines. This system computes the noise generated by turbulence impinging on the leading edges of the fan and fan exit guide vane, and noise generated by boundary-layer turbulence passing over the fan trailing edge. BFaNS has been validated on three fan rigs that were tested during the NASA Advanced Subsonic Technology Program (AST). The predicted noise spectra agreed well with measured data. The predicted effects of fan speed, vane count, and vane sweep also agreed well with measurements. The noise prediction system consists of two computer programs: Setup_BFaNS and BFaNS. Setup_BFaNS converts user-specified geometry and flow-field information into a BFaNS input file. From this input file, BFaNS computes the inlet and aft broadband sound power spectra generated by the fan and FEGV. The output file from BFaNS contains the inlet, aft and total sound power spectra from each noise source. This report is the second volume of a three-volume set documenting the Broadband Fan Noise Prediction System: Volume 1: Setup_BFaNS User's Manual and Developer's Guide; Volume 2: BFaNS User's Manual and Developer's Guide; and Volume 3: Validation and Test Cases. The present volume begins with an overview of the Broadband Fan Noise Prediction System, followed by step-by-step instructions for installing and running BFaNS. It concludes with technical documentation of the BFaNS computer program.

15. SUBJECT TERMS
Fan blades; Vanes; Broadband; Turbulence; Rotor stator interactions

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