Engine Cooling Fan Structural Analysis –SAE J1390 APR82

SAE Recommended Practice
Approved April 1982

THIS IS A PREPRINT WHICH IS SUBJECT TO REVISIONS AND CORRECTIONS. THE FINAL VERSION WILL APPEAR IN THE 1983 EDITION OF THE SAE HANDBOOK.

SAE *The Engineering Resource For Advancing Mobility*

PREPRINT

ENGINE COOLING FAN STRUCTURAL ANALYSIS—SAE J1390 APR82

SAE Recommended Practice

Report of the Engine Committee, approved April 1982.

"This SAE Recommended Practice is intended as a guide toward standard practice but may be subject to frequent change to keep pace with experience and technical advances, and this should be kept in mind when considering its use."

1. Purpose—The purpose of this recommended practice is to identify the general methodology for the structural analysis of engine cooling fans, and to provide expanded information on subset practices within the general methodology, such that a user of this practice can adapt specific subsets related to a vehicle[1] class.

2. Overall Scope—Three levels of fan structural analysis are included in this practice:

(a) Initial Structural Integrity
(b) In-vehicle Testing
(c) Durability Test Methods

The Initial Structural Integrity section describes analytical and test methods used to predict potential resonance and therefore possible fatigue accumulation.

The In-vehicle (or machine) section enumerates the general procedure used to conduct a fan strain gage test. Various considerations that may affect the outcome of strain gage data have been described for the user of this procedure to adapt/discard depending on the particular application.

The Durability Test Methods section describes the detailed test procedures that may be used depending on type of fan, equipment availability, and end objective.

Each of the above levels builds upon information derived from the previous level. Engineering judgment is required as to the applicability of each level to a different vehicle environment or a new fan design.

This recommended practice is applicable to heavy duty trucks, construction equipment, industrial and agricultural equipment. It does not necessarily include passenger cars and light trucks.

3. Initial Structural Integrity

3.1 Scope—It is necessary to identify and attempt to evaluate the characteristics of an application which can have an effect on fan durability. Failures almost always occur in fatigue, so careful attention should be paid to avoid resonance or forced vibration of the fan. This section considers vibrational inputs, fan natural frequencies, and operating speed as part of the initial structural integrity analysis. A fan application fact sheet (Table 1) is recommended as a form to communicate between user and fan supplier.

3.1.1 A resonant condition may occur when the natural frequencies of the fan as determined from paragraph 3.3 is coincident with either of the vibrational input frequencies or their harmonics, as calculated in paragraph 3.2. Therefore, it is desirable to separate these frequencies, including the upper and lower harmonics, whenever possible. In addition, torsional vibrations, auxiliary equipment, driveline vibrations, etc., may cause vibratory inputs to the fan which cannot be predicted in equation form.

3.2 Vibrational Inputs

3.2.1 Without verification by in-vehicle testing, the potential critical speeds and frequencies that can affect the fan can only be predicted. Equations 1 and 2 are used to calculate the piston firing and blade pass frequencies (in Hz). The blade pass frequency is associated with obstructions which cause a non-uniform or "pulsating" flow as the fan rotates. These equations are more applicable to fans whose blades are evenly spaced.

$$F_{pf} = \frac{(\text{No. of Cylinders})\ (\text{Engine rpm})}{(30)\ (\text{No. of Cycles})} \quad (1)$$

where number of cycles refers to a 2 or 4 stroke engine

$$F_{bp} = \frac{(\text{Fan rpm})\ (\text{No. of Blades})}{(60)} \quad (2)$$

3.3 Fan Natural Frequencies

3.3.1 The resonant frequencies and location of the node lines of a fan should be measured. This can be done by using a shaker table, accelerometers, strain gages, or by visual observation. The natural frequency of a fan can, and usually will, be affected by the following:

(a) The shape of the fan mounting surface, which should be duplicated as closely as possible;
(b) Torque of the mounting bolts;
(c) Level of excitation when using a shaker; and
(d) Dimensional variations from fan to fan, including material tolerances.

3.3.2 Most natural frequencies of a fan will change slightly as the rotational speed of the fan is varied. The following equation may be used to estimate the change in frequency with rotation (Hz):

$$F_{rotating} = \sqrt{F^2_{static} + \frac{rpm^2}{3600}} \quad (3)$$

3.3.3 Finite element analysis methods may be used as an alternative or adjunct to test methods. Mode shapes and frequency, and relative stress gradients can be numerically predicted and compared to vehicle vibrational inputs.

3.4 Operating Speed

3.4.1 It is desirable to keep the fan operating speed as low as possible to minimize stresses due to centrifugal force.

3.5 Log Sheet

3.5.1 The fan user and supplier may wish to establish a fan application fact sheet. This can be used to identify design parameters which affect fan performance for their particular application and to record the basic fan characteristics. It must be remembered, however, that one cannot anticipate all of the factors that will affect fan durability while early in the design stage. No itemized list will be all-inclusive, and no algorithm is possible. A sample fact sheet is provided as Table 1. Users should feel free to modify it as mutually desired.

4. In-Vehicle Test

4.1 Scope—In-vehicle tests can be used to complement the Initial Structural Integrity section of this practice because the forces on a fan are determined by a combination of the fan's operating environment and the engine/vehicle operational duty cycle conditions. A fan designed for a specific vehicle application and having satisfactory structural strength in its intended application, may have unsatisfactory durability in a different application. The following sections will aid in the selection of a suitable test vehicle, in the preparation and instrumentation of the vehicle for test, and in conducting the actual test.

4.2 Test Vehicle Selection—This subsection considers the kinds of standard and optional vehicle equipment which can impose forces, vibrations, and frequencies on the subject fan. The vehicle equipment environment influences the fan by three different methods. Equipment obstructions ahead of, behind, and around the fan disturb the air flow passing through the fan. This air flow disturbance imposes forces and vibrations on the fan. The engine and other equipment are sources of mechanical vibrations. These vibrations can propagate and be transmitted to the subject fan through its mounting attachment. The fan drive which determines the plane-of-rotation, the center-of-rotation, and the rotational speed directly induces inertial forces and vibrations in the subject fan. Consideration of these factors will permit the tester to specify the appropriate optional equipment for the test vehicle.

4.2.1 Package Obstructions—Equipment located in the near vicinity of the fan that restricts and obstructs the fan air flow.

4.2.1.1 *Radiator Core*—Consider the variation in air flow restriction due to optional radiator cores with a different number of tube rows, fin densities, and fin designs. Radiator tanks, side structures, and cross-reinforcing rods can be significant obstructions if the fan partially "sweeps" any of these items.

4.2.1.2 *Heat Exchanger Core*—Any finned core located ahead or behind the fan will restrict air flow. Examples are air conditioning freon condensor and coolers for engine lubricating oil, power steering fluid, automatic transmission fluid, and hydraulic PTO fluid.

4.2.1.3 *Shroud*—Optional fan shroud or hand guards.

4.2.1.4 *Radiator Shutters*—Mounting location (in front or behind radiator) and type (modulating or full open-full closed).

4.2.1.5 *Winter Front*—Optional grille mounted winter fronts.

4.2.1.6 *Blockage*—Frame member or body sheet metal obstructions. Also belt pulleys and crankshaft damper can present circular section blockages in close proximity.

[1] The term "vehicle" as used in this practice, is defined as an all-inclusive term. "Vehicle" includes the SAE J687 definition of vehicle and the SAE J1057, J1116, and J1234 definitions of machine.

TABLE 1—FAN APPLICATION FACT SHEET

PART ONE—FAN USER INFORMATION

Customer: ______
Location: ______
Contact: ______
Phone No.: ______
Performance Reqd. Speed ______ rpm
______ CFM at ______ in H_2O SP
Air Density: ______ Est. hp ______
Limitations
Max. Dia. ______ Overspd.: ______
Max. P.W. ______ Max. hp ______
Other
______
______
______
______

Reqd. Testing
______ Airflow ______ Spin Pit
______ Shaker Scan ______ Strain Gage

Application Description
Model No. ______
Engine: ______
Rated hp: ______ at rpm ______
Drive Type: ______
Fan Drive Ratio: ______
Fan Mtg. Loc.: ______
Fan Rotation: ______
Pilot and Bolt Circle: ______
Max. Runout: ______
Belt Tension: ______
System
Shroud: ______ Dia. ______ Type ______
Fan Position: ______
Clearance*: ______ Fr ______ Rr ______

______ Endurance ("Bench Test")
______ Other: ______

PART TWO—FAN SUPPLIER INFORMATION

Manufacturer: ______
Location: ______
Contact: ______
Phone No.: ______
Proposal
Mfr. P/N ______
Drawing Attached: ______
Fan Wt.: ______ Inertia ______
Max. Fan Unbalance ______
Other ______

Test Results Attached
______ Airflow Performance
______ Shaker Scan
______ Spin Pit Burst Speed (Act. or Calc.)
______ Strain Gage Data
______ Material Properties
______ Endurance ("Bench Test")
______ Other: ______

* Clearance from fan mounting face to nearest obstructions. The proximity of the blades to obstructions should be discussed with the fan vendor.

4.2.1.7 *PTO Shafts*—Front crankshaft driven power take-off shaft.

4.2.1.8 *Deflector*—Optional fan blast deflector.

4.2.2 VIBRATION SOURCES—Equipment that generates mechanical vibrations. Because these equipment items are commonly located in the immediate vicinity of the fan, they also cause fan air flow obstruction effects.

4.2.2.1 *Engine*—Design parameters and/or data permit the tester to consider engine vibration magnitudes and fundamental forcing frequencies.

4.2.2.1.1 Type—Gasoline or diesel, two-stroke cycle or four-stroke cycle, number of cylinders, in-line or Vee, turbocharged or naturally aspirated, uniform or uneven cylinder firing interval.

4.2.2.1.2 Size—Displacement, bore, stroke, and horsepower rating.

4.2.2.1.3 Crankshaft Damper—Determine if a damper is provided, and location of fan drive pulley with respect to damper (is fan driven from crank or damper inertia member?).

4.2.2.1.4 Speed—Governed or rated engine speed; fast idle or sub-idle.

4.2.2.1.5 Vibration Data—Review any available vibration test data for magnitudes and frequency. Crankshaft torsional data is important.

4.2.2.2 *Accessories*—Power steering pump, air brake compressor, freon compressor, alternator, emissions air pump, vacuum brake pump, and hydraulic brake booster pump.

4.2.2.3 *Driveline*—Optional sizes, lengths, and types (one-piece or two-piece).

4.2.3 FAN DRIVE—The drive ratio and clutch, if used, control fan rotational speed. Additionally, the drive acts as the path to transmit mechanical vibration to the fan.

4.2.3.1 *Type*—Gear or belt, fixed or clutch (on-off, modulated engagement or viscous).

4.2.3.2 *Ratio*—Fan speed to engine speed ratio.

4.2.3.3 *Position*—Fan mounting position on end of crankshaft, on water pump shaft, or remote mounted fan spindle.

4.2.3.4 *Fan Mounting*—Fan mounting surface or spacer configuration.

4.3 Instrumentation—This section considers the preparation and instrumentation of the subject fan and the selected test vehicle.

4.3.1 STRAIN GAGE LOCATION—It is important that strain gages are placed at all of the highly stressed locations on the subject fan. Several methods exist for gage location. The best procedure is to employ multiple methods of gage location and to use a generous number of gages. This will reduce the risk that a highly stressed location has been overlooked. The fully strained gaged fan becomes in effect a "master fan." It should be handled carefully during the in-vehicle test and should be safely stored after test completion. Retention of the "master fan" will allow for its use in future in-vehicle tests or to correlate bench durability tests.

4.3.1.1 *Brittle Lacquer*—Strain gage locations are determined by crack patterns developed in the brittle lacquer coating. The brittle coating can be patterned in the test vehicle and/or on a bench test stand. The bench procedure can use rotational and/or axial excitation.

4.3.1.2 *Judgement*—Gage locations determined by past experience with similar fan designs or by analytical analysis of the subject fan design. Contact fan supplier for gage location information.

4.3.1.3 *Modal Analysis*—Gage locations are along the node lines of the principal modes that are expected to receive the largest amounts of vibrational energy.

4.3.1.4 *Finite Element*—Gage locations are determined from the computer analysis of a finite element model of the subject fan.

4.3.1.5 *Photoelastic*—Gage locations are determined from the bi-refringent pattern in a photoelastic coating on the subject fan.

4.3.1.6 *Failures*—Gage locations determined by the fatigue crack pattern in a failed fan.

4.3.2 RECORDED DATA—Suitable instrumentation is required to record engine speed, fan speed when a viscous drive is used, and strain gage output magnitude and frequency. For a viscous drive, sensor air temperature and clutch housing temperature may be recorded. For a plastic fan, the adjacent air temperature and the plastic material temperatures are required.

4.3.3 VEHICLES' MEASUREMENTS—Specific measurements may be made on the selected test vehicle so that the following factors will be known.

4.3.3.1 *Driveline*—Record out-of-balance and verify correct alignment and universal joint phasing.

4.3.3.2 *V-Belts*—Adjust belt tension on all accessory drives including the fan drive to the specified maximum. New V-belts require "break in." Tension new belts 50% higher than normal maximum specification and run for ½ h. Readjust tension to specified maximum.

4.3.3.3 *Fan Mounting*—Record the axial runout of the fan drive mounting surface and the radial runout of the fan drive pilot.

4.3.3.4 *Fan to Shroud*—Record radial tip clearances. Record axial depth of fan penetration into shroud.

4.4 Vehicle Test—The intent of the in-vehicle fan test is to record fan strains while vehicle operational duty cycle conditions and the fan operating environment are varied in a systematic way. This will determine the combination of factors that cause the highest fan strains.

4.4.1 VIBRATION SOURCES—Determine the effect on fan strains for different vibration input conditions.

4.4.1.1 *Engine Load*—Test with engine at full load, partial load, and no load conditions.

4.4.1.2 *Engine Speed*—Test condition of maximum speed (governed speed or rated speed and a specific overspeed) and speed transients due to automatic or manual transmission shifting. Test engine start-up, shutdown, idle, and specific below idle speed conditions. Scan the engine operating speed range in a continuous sweep mode in each transmission gear position to identify fan resonances and maximum fan strain amplitudes.

4.4.1.3 *Accessories*—Test the effect of the various accessories on-off duty cycle.

4.4.1.4 *Fan Clutch*—Determine the effect of the fan clutch operating modes. For non-viscous clutches—lockup operation and on-off transients. For viscous clutches—disengaged, fully engaged, and mechanically locked operation.

4.4.1.5 *Fan Drive*—Test with fan mounting components (water pump, spacer, fan drive) that produce the maximum allowable radial and axial runout.

4.4.1.6 *Driveline*—Test with a known added amount of out-of-balance or out-of-phase universal joints.

4.4.1.7 *V-Belts*—Test with both a "loose" belt tension condition and with an over-tightened belt tension condition. This is applicable to the fan drive belts and to all accessories.

4.4.1.8 *Fan*—Test with the maximum allowable out-of-balance.

4.4.2 Obstructions—Determine the effect on fan strains caused by obstruction changes.

4.4.2.1 *Accessories*—Selectively remove individual accessories to determine their obstruction effect on fan strains.

4.4.2.2 *Radiator Core*—Determine effects of change in air flow restriction caused by an optional core. Simulate the restriction increase due to core clogging in service.

4.4.2.3 *Radiator Shutters*—Effects of shutters open, closed, and partially open if the modulating shutter type is used.

4.4.2.4 *Winter Front*—Test the effect on fan strains caused by the use of winter fronts or cardboard.

4.4.2.5 *Shroud*—Test for the effects of an optional fan shroud.

4.4.2.6 *Heat Exchanger Core*—Test for the obstruction effect on fan strains by selectively removing optional heat exchanger cores.

4.4.3 In-Service Evaluation—Simulate special conditions occurring during typical vehicle operation.

4.4.3.1 *Shock*—Effects on road, cargo loading, or auxiliary equipment caused shock inputs.

4.4.3.2 *Water Splash*

4.4.3.3 Dirt build-up on fan blades.

4.5 Analysis—The strain data gathered during in-vehicle testing must be analyzed to be useful to the engineer. SAE J1099, "Technical Report on Fatigue Properties" provides information that is useful in the analysis of service load and/or strain data. It also contains a list of references that have proven useful in the analysis of fatigue data.

5. Durability Test Methods

5.1 Scope—Durability tests can be used to complement in-vehicle strain gage testing. Testing can also evaluate areas unaccessible to conventional strain gage measurements. Durability testing, with the ability to control and increase strain levels, can demonstrate design factors at loads greater than anticipated service. Bench testing allows evaluation of the fan at a greatly accelerated rate compared to most in-vehicle field testing.

5.2 Methods—A variety of bench tests are used to evaluate fans. It is difficult for any one test to accurately reproduce every operating characteristic. The user must select the method(s) that satisfy his/her durability criteria. Since it is accepted that fan durability considerations are associated with fatigue, the methods outlined are generally designed to evaluate endurance characteristics.

5.2.1 Non-Rotational Resonant Test—The test fan is mounted at the pilot and bolt circle and loaded axially through the range of amplitude and frequencies of interest. This method may not accurately reproduce all modal conditions and will not include strains produced by centrifugal loading.

5.2.1.1 *Equipment* (*Shaker Table*)—The vibrator should be capable of accepting various fan mounting arrangements with normal input loading from 10–100 lb and a frequency range of 25–500 Hz.

5.2.1.2 *Instrumentation*—A method of monitoring frequency and strain amplitudes that will accurately relate the test conditions to the in-vehicle conditions is required. Additionally, the use of a strobe light and frequency analysis may aid in the test evaluation.

5.2.1.3 *Procedure*—The fan must be mounted using an actual attachment component from the vehicle (that is, hub, spacer, clutch, etc.). This assembly is mounted to the driving member of the loading source. If the test assembly must be suspended, use caution to minimize the frequency effects on the test results.

5.2.1.4 *Durability Test*—Mount the "master fan" used in the vehicle analysis and set the test stand to simulate the frequency mode of vibrating and the highest dynamic strain level observed during the vehicle test. Because the minor variations of physical conditions of nominally identical parts can cause small changes in resonant frequencies, each test fan should be gaged to insure operation at the required test condition. Replace the "master fan" with the test fan and adjust frequency if necessary to maintain peak resonance. Other than frequency, all test conditions must remain as set up with the master fan. Monitor equipment to insure that conditions remain stable during testing. Strain levels higher than anticipated can also be tested.

5.2.2 Rapid Cycle Test—This test rotates the fan from zero or a low speed to some predetermined maximum speed and back again. The test has limited applications, but can be used for flex fans and to simulate some unusual in-vehicle situations primarily encountered with viscous drives and other add-on clutches.

5.2.2.1 *Equipment*—Test stand can be driven with an electric motor and should be capable of adjusting the acceleration, maximum speed, deceleration, and dwell time. Test stand power requirements may be substantially higher than the in-vehicle rating of the fan.

5.2.2.2 *Instrumentation*—A method of monitoring frequency and strain amplitudes that will accurately relate the test conditions to the in-vehicle conditions is required. The use of a strobe light and frequency analyzer may aid in the test evaluation. Additionally, methods of measuring speed and acceleration/deceleration will be required.

5.2.2.3 *Procedure*—The fan must be mounted using an actual attachment component from the vehicle (that is, hub, spacer, clutch, etc.). This assembly is mounted to the drive shaft. Use caution to minimize the frequency effects of the slip ring or adapters on the test results.

5.2.2.4 *Durability Test*—Mount the "master fan" that was used in the vehicle analysis and adjust the test stand to duplicate both frequencies and highest strain levels observed during the vehicle test. Replace the "master fan" with a test fan before testing. Monitor acceleration, speeds, and deceleration to insure that conditions remain stable during the test.

5.2.3 Torsionally Loaded Rotating Test—This test rotates the fan at some constant operating speed while applying a torsional vibration to the drive shaft. The test can accurately duplicate centrifugal loads while accumulating stress cycles very rapidly. Durability of the test equipment can be a problem.

5.2.3.1 *Equipment*—The test stand can be driven with an electric motor. The fan shaft may be driven through "U" joints or off-center pulleys or other methods to produce the torsional loads. Hydraulically driven, torsional actuators are also available with load and frequency capabilities suitable for fan testing. Speed and power capabilities should reproduce all possible vehicle conditions. It should be noted the "U" joint excited tests may be limited to lower fan speeds because of joint durability problems.

5.2.3.2 *Instrumentation*—A method of measuring speed, frequency, and strain amplitude that will accurately relate the test conditions to the in-vehicle conditions is required.

5.2.3.3 *Procedure*—The fan must be mounted using an actual attachment component from the vehicle (that is, hub, spacer, clutch, etc.). This assembly is mounted to the drive shaft. Use caution to minimize the frequency effects of the slip ring or adapters on the test results.

5.2.3.4 *Durability Test*—Mount the "master fan" used in the vehicle analysis and set the test stand to simulate the frequency and speed at the highest strain levels observed during the in-vehicle test. Because the minor variations of physical conditions of nominally identical parts can cause small changes in resonant frequencies, each test fan should be gaged to insure operation at the required test conditions. Normally one to four gages are sufficient. Replace the "master fan" with a test fan and adjust the speed, if necessary, to maintain peak resonance. All other conditions must remain as established with the "master fan." Monitor equipment to maintain stability during testing. Strain levels higher than anticipated service can also be tested.

5.2.4 Obstruction Loaded Rotating Test—This test rotates the fan at some constant operating speed while applying air loaded vibrations by placing obstructions in front and/or behind the fan. The test can accurately duplicate centrifugal loads while accumulating stress cycles very rapidly.

5.2.4.1 *Equipment*—The test stand can be driven with an electric motor. Radiators, shutters, shrouds, and other vehicle components can be used as obstructions. Additional obstructions extended radially can be evenly or unevenly spaced and used to further increase strain levels. Speed and power capabilities should reproduce all possible vehicle conditions.

5.2.4.2 *Instrumentation*—A method of measuring speed, frequency, and strain amplitude that will accurately relate the test conditions to the in-vehicle conditions is required.

5.2.4.3 *Procedure*—The fan must be mounted using an actual attachment component from the vehicle (that is, hub, spacer, clutch, etc.). This