AERODYNAMIC LIMITATIONS OF FLIGHT

I. Any force applied to deflect an airplane from a straight line produces a stress on its structure due to inertia. The amount of this force is called load factor.

A. Load factor is the ratio of the total load supported by the airplane’s wings (i.e., lift) to the actual weight of the airplane and its contents:

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\text{Load factor} = \frac{\text{Total load supported by the wings}}{\text{Total weight of the airplane}}
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1. EXAMPLE: An airplane has a gross weight of 2,000 lb. During flight it is subjected to aerodynamic forces, which increase the total load that the wing must support to 4,000 lb. The load factor is thus 2.0 (4,000 ÷ 2,000). The airplane wing is producing lift equal to twice the gross weight of the airplane.

B. Load factor can also be expressed as the ratio of a given load to the pull of gravity, expressed in “Gs.” If the weight of the airplane is equal to 1 G, and if a load of three times the actual weight of the airplane were imposed upon the wing due to a curved flight path, the load factor of 3 is expressed as 3 Gs.

C. In unaccelerated flight, the airplane is said to have a load factor of 1; i.e., the total lift that the wings are producing is equal to the gross weight of the airplane. If the angle of attack of the wings is increased while airspeed remains constant, e.g., in a pull-up from a dive, the wings produce more lift and thus a higher load factor.

D. A positive load occurs when back pressure is applied to the elevator, causing “centrifugal force” to act in the same direction as weight. A negative load occurs when forward pressure is applied to the elevator control, causing “centrifugal force” to act in a direction opposite to that of weight.

II. Load Factors and Airplane Design. In order to be certified by the FAA, airplanes must conform with prescribed structural strength (i.e., maximum allowable load factor) standards set forth by Federal Aviation Regulations. Airplanes are classified as to strength and operational use by means of the category system. Most general aviation trainer-type airplanes are classified in one or more of the following categories:

A. The normal category has a maximum limit load factor of 3.8 positive Gs and 1.52 negative Gs. A limit load factor is the highest positive or negative load factor that can be sustained without causing permanent deformation or structural damage to the airplane. The limit load factors listed for each airplane category represent the maximum load factors (both positive and negative) that can be expected in typical operations for that category of airplane. Permissible maneuvers in the Normal category include: Any maneuver incidental to normal flying, stalls, lazy eights, chandelles, and steep turns in which the angle of bank does not exceed 60°.

B. The utility category has a maximum limit load factor of 4.4 positive Gs and 1.76 negative Gs. Permissible maneuvers in the utility category include: All operations in
the normal category, spins (if approved for that airplane), lazy eights, chandelles, and steep turns in which the angle of bank is more than 60°.

C. The **acrobatic category** has a maximum limit load factor of 6.0 positive Gs and 3.0 negative Gs. There are no restrictions except those shown to be necessary as a result of required flight tests.

D. The category system indicates what operations can be performed in a given airplane without exceeding load factor limits. You must operate the airplane within the load factor limits for which it was designed so as to enhance safety while still benefiting from the intended use of the airplane. An airplane’s structure is designed to support a certain total load. It is therefore vital to observe maximum gross weight limits as well as load factor limits.

III. **Effect of Turns on Load Factor.** A turn is made by banking the airplane so that lift from the wings no longer acts straight up, but acts upward at an angle. In this orientation, the horizontal component of lift pulls the airplane around the turn from its straight flight path.

A. In a constant altitude coordinated turn, the resultant load is the result of two forces -- weight and the apparent “centrifugal force” as shown below.

B. The airplane’s wings must produce lift equal to the resultant load in a level, coordinated turn. As the required lift increases, load factor also increases. Thus, a level, coordinated turn produces a load factor that is greater than 1 G.

C. In any airplane, if a constant altitude is maintained during the turn, the load factor for a given degree of bank is the same. This is because the vertical component of lift (which must always equal the airplane’s weight in level flight), and therefore the total lift required, remain the same regardless of the airspeed and rate of turn. The horizontal component of lift thus also remains constant for any given bank angle.
because of the fixed relationship between the vertical component of lift and the total lift required. Because the total lift required in a level turn does not vary for any given bank angle, the load factor remains constant.

D. Using the figure below, it is clear that the load factor increases at a rapid rate after the angle of bank reaches 60°. The wing must produce lift equal to this load factor if the airplane is to maintain altitude.

1. The figure below can be used to see why the maximum bank angle for normal-category airplanes is 60°. The 60° angle of bank produces a load factor of 2.0. The positive limit load factor of 3.8 Gs for normal-category airplanes is exceeded at approximately 75° of bank, an increase of only 15° beyond the maximum-allowable bank angle of 60°. Caution dictates a margin of safety between the maximum-allowable bank angle and the bank angle at which structural damage will occur.

2. At an angle of bank of slightly more than 80° in level flight, the load factor exceeds 6.0, which is the limit load factor of an acrobatic airplane.
IV. Effect of Load Factor on Stalling Speed. Any airplane, within the limits of its structure and the strength, can be stalled at any airspeed. At any given airspeed, the load factor increases as angle of attack increases, and the wing stalls when the angle of attack has been increased beyond the critical angle. Therefore, there is a direct relationship between the load factor imposed upon the wing and its stalling characteristics.

A. The airplane’s stall speed increases in proportion to the square root of the load factor.

EXAMPLE: Using the load factor chart above, the load factor produced in a 75° banked, level turn is 4.0. The square root of 4 is 2. An airplane that has a normal unaccelerated stall speed of 45 kt. will stall at 90 kt. when subjected to a load of 4 Gs.

2. You can also use the load factor chart to observe why 30° is typically considered the maximum safe bank angle in the traffic pattern. At bank angles greater than 30°, the load factor (and thus, the stall speed) begins to increase rapidly.

V. Maneuvering Speed. The maximum speed at which an airplane can be stalled without exceeding its structural (or load) limits is the maneuvering speed (VA).

A. VA can also be defined as the minimum airspeed at which the wing can produce lift equal to the positive limit load factor.

B. When operating below VA, a damaging positive flight load cannot (theoretically) be produced. The airplane should stall before the load becomes excessive. Any combination of flight control usage, including full deflection of the controls or gust loads created by turbulence, should not create an excessive air load if the airplane is operated below VA. CAUTION: Certain adverse wind shear or gusts may cause excessive loads even at speeds below VA.

C. VA is a vital reference point for pilots, but it is not marked on the airspeed indicator since it varies with gross weight. VA can be found in the Pilot’s Operating Handbook (POH) for each airplane and/or on a placard within the cockpit. VA decreases with gross weight because it is effectively an accelerated stall speed. Just as VS0 and VS1 decrease as gross weight decreases, VA decreases as gross weight decreases.

D. Older general aviation airplanes may not have a published VA in their POHs. In this case, a general rule for determining the maneuvering speed is approximately 1.7 times the normal stalling speed.

EXAMPLE: An airplane that normally stalls at 35 kt. should never be stalled when the airspeed is above 60 k (35 kt. x 1.7 = 59.5 kt.).

VI. Effect of Turbulence on Load Factor. Turbulence in the form of vertical air currents can, under certain conditions, cause severe load stress on the airplane. For example, when an airplane flying at a high airspeed with a low angle of attack suddenly encounters an updraft, the relative wind changes to strike the bottom of the airfoil at a greater angle. This increases the wing’s angle of attack. All certificated airplanes are designed to withstand loads imposed by turbulence of considerable intensity. Nevertheless, gust load factors increase with increasing airspeed. Therefore, it is wise in extremely rough air, to reduce the speed to below VA.
A. As a general rule when severe turbulence is encountered, the airplane should be flown at or below $V_A$ as shown in the POH and/or on the placard in the airplane. This speed is the one least likely to result in structural damage to the airplane (even if the control surfaces are fully deflected), yet it allows a sufficient margin of safety above stalling speed in turbulent air.

B. Avoid over-stressing the airplane in severe turbulence by maintaining a level attitude and accepting variations in altitude and airspeed.

VII. V-G Diagram (Velocity versus G Loads)
A V-G diagram is a graphic representation of the operating limitations of a specific make and model of airplane under specified conditions (e.g., weight and Configuration). Airplane manufacturers use numerous V-G diagrams when designing an airplane in order to define its airspeed and load factor limits. These limits specify that airplane’s flight, or operating, envelope.

A. See the V-G diagram shown below to observe several important operating limitations. Airspeed (V) is shown on the horizontal axis with load factor (G) on the vertical axis.

B. The curved lines starting at 0 on the vertical axis represent the positive and negative lines of maximum lift capability. These lines indicate the maximum amount of lift the airplane can generate at a specified speed. Note that at an indicated airspeed of zero, the wing generates zero lift. The intersection of the maximum lift line and a given airspeed line indicates the maximum load factor that can be placed on the airplane for
that speed. If any load factor greater than the maximum lift line is placed on the airplane at a given airspeed line, a stall will result. The solid horizontal lines at +3.8 G and −1.52 G represent the positive and negative limit load factors for this airplane, i.e., the limits for a normal category airplane. The dashed lines at +5.7 G and −2.28 G are the ultimate load factors, which are determined by multiplying the limit load factors by the required safety factor of 1.5. Any load placed on the airplane between the limit load factor and ultimate load factor may cause permanent deformation of the airplane’s primary structure (e.g., wings). A high rate of fatigue damage may be incurred, but the structure should not fail. However, the fatigue damage incurred may be of sufficient magnitude to cause structural failure later during completely normal operations.

A load placed on the airplane greater than the ultimate load factors will cause the wings to separate from the airplane. In smooth air and with the wings level, the airplane is flying at 1 G. The speed at which the airplane stalls at 1 G is $V_{S1}$. $V_{S1}$ is marked on the airspeed indicator at the lower limit of the green arc. $V_{S1}$ is shown on the V-G diagram by a solid vertical line. Any stall that occurs above 1 G is an accelerated stall.

$V_A$ is the airspeed that is at the intersection of the positive limit load factor and maximum lift lines. At speeds greater than $V_A$, the limit load factor will be exceeded (leading to structural damage or failure) before the airplane will stall. Certain airspeeds, called design airspeeds, are established when an airplane is designed (e.g., design maneuvering speed). Some important airspeed limitations are established from various design airspeeds and other factors.

$V_{NO}$ is the maximum structural cruising speed, or maximum normal operating speed, and is shown on the airspeed indicator at the upper limit of the green arc. $V_{NO}$ is shown on the V-G diagram by a solid vertical line. $V_{NO}$ is determined by the intersection of the negative limit load factor and the load produced by an instantaneous 30 ft.-per-second downdraft. The airspeed range from $V_{S1}$ to $V_{NO}$ is the normal operating range, which is considered safe for moderately bumpy air. Flight above $V_{NO}$ should be conducted only in smooth air and with caution.

$V_{NE}$ is the airplane’s never-exceed speed and is marked by the red line on the airspeed indicator. $V_{NE}$ is shown on the V-G diagram by a solid vertical line. If flight is attempted beyond $V_{NE}$, structural damage or failure may result from a variety of phenomena, even if excessive load factors are not imposed.

The airspeed range from $V_{NO}$ to $V_{NE}$ is the caution range, i.e., the yellow arc on the airspeed indicator. The airplane must be operated within the flight envelope to prevent the airplane’s primary structure from being deformed or damaged. Thus, the airplane in flight is limited to a regime of airspeeds and load factors that do not exceed either of the following:

1. The positive or negative limit load factors.
2. $V_{NE}$.