Improvements in Airplane Stopping Performance on Adverse Runways

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The basic elements affecting adverse runway stopping performance of modern aircraft are discussed in terms of pilot technique, runway environment, and brake control system. Impact of the various aircraft design decisions and requirements on the basic vehicle parameters is also is also discussed. Runway surface texture (microtexture, macrotexture), material, and design produce traction variations which must be considered in system development and operation. Pilot technique impacts system design philosophy and airplane operational performance. Final utilization of the available performance is dependent on the total system integration. Advances in braking systems for operation on adverse runways will require better system integration, understanding of environment, and additional tire data. In addition, increased emphasis should be placed on improving traction and pilot advisory information.

Introduction

THE typical commercial aircraft stopping system consists of air brakes, wheel brakes, and engine thrust reverser. Military airplanes often use parachute devices in addition to wheel brakes. This paper primarily discusses the braking system design, operation, and development. Since braking and steering are interdependent, the latter aspect will be discussed briefly.

The primary considerations for an airplane stopping system are safety and economics. The system must allow the airplane to operate reliably within intended runway length and width. Since material and equipment failures will occur, braking and directional control must be retained under failure conditions. Safety and reliability are achieved by system separation and adequate redundancy.

Brake System Development

Antiskid systems were originally intended to prevent prolonged skids and subsequent tire blowouts. This basic role has been expanded to include optimization of stopping performance under a variety of runway conditions, e.g., dry, wet, or icy. The development cycle of a brake system consists of many actions which occur at different times. The earliest item which gets firmed up is the location of nose and main gears. The typical range of the center of gravity during operational regime is also fixed. These items determine the main and nose gear loading, which have a major influence on braking and directional control. Other information available at this stage includes the expected tail size and basic aerodynamic characteristics necessary for calculation of aerodynamic performance and airplane stability during flight. Adequate heading control during takeoff in the presence of an engine failure is an important consideration and impacts tail size.

The early landing gear design efforts are mainly aimed at configuring a convenient way to stow the gear without excessive complexity of linkage, failure modes, and incurring any drag penalties. The system performance can be impacted by early landing gear design efforts. The gear attachment structure and gear height can impact gear fore and aft stiffness and weight transfer during braking. The basic configuration and torque reaction method can influence the truck pitch dynamics. About this time the shock strut characteristics also become matters of concern. The available stroke is nearly firm and all that needs to be done is to utilize it to minimize loads under extreme design conditions. The design sink rate is typically 10 fps for commercial transports while operational landings seldom exceed 1-2 fps. The braking system could greatly benefit if special attention is paid to the operational regime during the early trades used to configure metering pins. Special emphasis should be placed on minimizing rebound.

Once the landing gear configuration takes firm shape, other gear components also begin to be considered. Earliest item which receives attention is the brake since it is a long-lead-time item. Once developed the brake does not lend itself to adjustment of its basic characteristics. The primary consideration in brake development is the heat sink required to meet kinetic energy requirements during stopping, both landing and refused takeoff. This aspect deserves careful evaluation to assure adequate brake life in service.

The other aspects which have received little or no attention pertain to the brake torque requirements and other associated dynamic characteristics. The consequences of insufficient torque are obvious, so the designer may be tempted to specify an excessively high torque capability to make sure he avoids the problem. Unfortunately, this approach can induce a difficult skid control problem on slippery runways (icy, wet, etc.) The skid control system will be forced to control at extremely low pressures, which may be in an area of the brake pressure/volume curve that is highly nonlinear, resulting in reduced efficiency. Care must also be taken to minimize the nonlinear area of the pressure/volume curve to insure satisfactory response in the low-pressure region. The type of brake lining selected can also impact brake dynamics, gear dynamics, and brake control system response. The noise content of the lining selected should be carefully assessed to assure a squeal- and chatter-free brake.

The tire is another crucial element which is selected early in the design cycle. The primary consideration is its load-carrying capability during the speed regime normally applicable for landing or takeoff cycles. The tire specifications provide roll tests simulating landing, taxi, and takeoff loads and speeds. The tests are largely tire structural integrity tests and very little is known about tire wear, cut resistance, or its traction characteristics after the qualification tests are complete.

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Other considerations in the selection of the tire include flotation and stowage requirements. The traction characteristics are seldom considered. This aspect is important and requires a careful trade. A high-pressure tire results in favorable wet runway traction and helps the designer in reducing his stowage requirements, but it increases tire wear on dry runways and aggravates flotation. A tire custom tailored for each aircraft provides the best solution. The tendency to select an off-the-shelf tire is motivated by cost savings in procuring original equipment and perhaps assuring commonality with other fleets. Problems arising from such trades seldom justify this penny-wise attitude.

With the release of major landing gear design drawings and specifications related to tire, wheel, and brake, attention now turns to other aspects of the system. The brake hydraulic system is configured along with the steering hydraulic system. The line lengths and sizes are firmed up to assure adequate power for various flight controls and auxiliary functions. This is the time for the landing gear designer to make his requirements known and to receive special consideration consistent with his needs. The proper sizing of the hydraulic system at this time will assure adequate system response and avoid costly and difficult changes later in the development of the system. The system redundancy, power supplies, indication system, and other interface requirements are also firmed up.

It is now time for release of skid control and steering component specifications. The discussion of these specifications and the role they play in successful design will be relegated to a later section so as to provide some discussion of the many variables which impact skid control performance. Proper understanding of these variables and their role in an important prerequisite to writing a good specification.

The environment in which aircraft operate places further constraint on system design. So far, we have discussed constraints imposed on the system during early aircraft design. These are necessary as the aircraft is mainly designed to be an efficient flying vehicle. Among the elements that require consideration are: runway traction and pilot technique.

Runway Traction

Various aircraft may operate into a variety of airfields, with commercial operations involving primarily asphalt and concrete runways. Some commercial operators do operate into grass and gravel fields. Military operations often necessitate use of quickly prepared rough-dirt fields. The diversity in runways materials provides a wide variety of traction characteristics.

Concrete and asphalt runways provide good flotation, runway life, and traction when surfaces are dry. In the presence of ice, snow, slush, and rain the available friction capability degrades. In addition, on wet runways a phenomena called "hydroplaning" can occur. The incidence of hydroplaning can be reduced by selection of suitable tire design, improvement of runway micro and macro-texture, and a good runway maintenance program.

Poor runway design can result in an almost complete absence of friction at high speeds on extremely wet runways. This situation may cause a loss of the locked-wheel protection devices which normally assure safe operation. The various studies conducted by NASA, FAA, and USAF[1,2]‡ have verified this, and runways with good traction have been stressed.

Several new runway concepts are being actively studied by USAF, such as porous surface runways. FAA favors the use of grooved runways. These runways provide a positive path for water to drain away and thus offer higher traction under similar rain condition. A good maintenance program is considered integral to any of these concepts. In the absence of such a program, rubber deposits and other contaminants can build up. In the presence of moisture this results in slippery conditions. Several excellent studies have been undertaken to acquire a better understanding of traction, and landing gear designers will greatly benefit from acquiring better understanding of this problem.

‡These papers include a comprehensive list of references on this subject.

Unprepared Fields

Generally speaking, unprepared runway traction is not too well understood. Available data are scant and more test data are needed to develop efficient systems for operation on such airfields. The available cornering data are sketchy under all conditions of operation. The available data indicate that traction on unprepared fields is marginal. The presence of excessive moisture causes degradation in both flotation and traction capabilities of the soil. Grass cover also makes the runway very slick in the presence of water. Good drainage is necessary to provide improved traction. This can be accomplished with a surface layer of gravel, provided no ruts or low spots are allowed to develop. Soft fields add another dimension to the problem.

Impact of Pilot Technique

Besides elements, such as runway traction or cross-wind, the pilot is perhaps the most significant external influence. The pilot influences the landing and takeoff field length requirements in several ways.

One of the elements of concern is late touchdown, which uses up much of the available runway, thus reducing the margin of safety. This problem is merely the inverse of another problem in which he may land short. Thus, precise landing aids permitting an all-weather landing capability are needed.

For purposes of this discussion it is assumed that such a problem is recognized and will be handled before too long to the satisfaction of all concerned. Even if a precise touchdown is assumed the pilot still can land hard and at excessive speeds. The landing technique, besides losing precious available distance, may cause undesirable rebound and make early braking and cornering difficult. The landing gear, thus, has to be designed for some abuse margin and metering pin analysis should carefully assess operational performance along with the critical design condition where peak load values are the primary concern.

Whereas the pilot exercises braking by merely depressing the brake pedals, the timing and manner in which he uses these is critical. On dry and good traction runways he can depress pedals firmly to help achieve optimum stopping. On wet runways, where excessive water is present or on very slippery runways (icy) he should apply brakes gradually. By partial but early brake application he can get some braking while preventing wheel lockups. As the skid control system adjusts to the prevailing conditions, the pilot can increase available brake pressure by depressing the pedals further.

Even though good runways may be available at sometime in the future and pilot advisory information and training may be improved, the skid control systems must be so designed as to cope with varying conditions of available traction. Presence of paint markings, tar strips, and puddles, along with differences in micro-texture/macro-texture and drainage will necessitate continuous updating in technology.

It was mentioned earlier that braking and cornering are related. This arises from the simple premise that the same vector must be shared for traction and cornering (Fig. 1). As demand in braking mode increases, the vector available for cornering decreases. Fortunately, as demand is placed in the cornering sense the skid control system will reduce braking effort due to its inability to assess excessive slip in the directional sense. The directional control of aircraft may be divided into high-, intermediate-, and low-speed regime. At

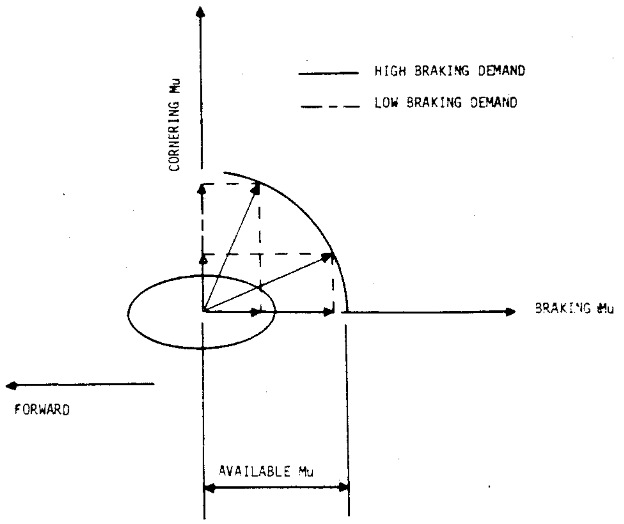

Fig. 1 Relationship between braking and cornering mu.

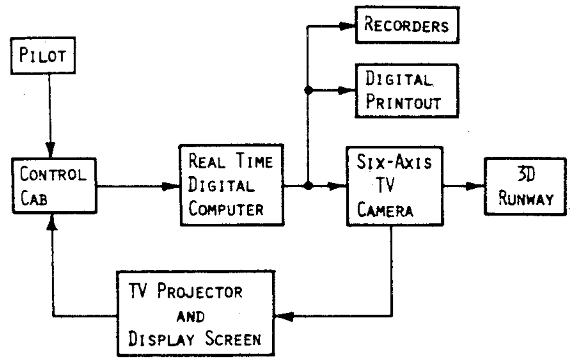

Fig. 2 Ground handling simulator schematic.

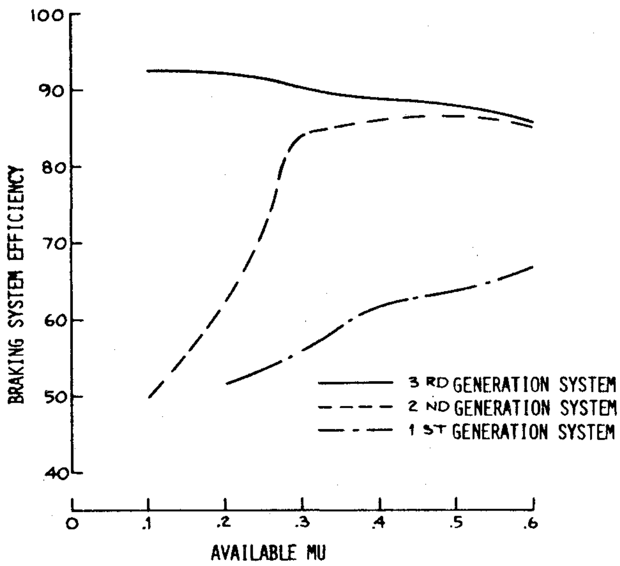

Fig. 3 Antiskid system efficiency improvements.

higher speeds considerable aerodynamic control is available, but as speed decreases to the intermediate range, the nose gear steering becomes the primary means of controlling aircraft heading. At low speeds turning is accomplished by using nose gear steering system assisted by differential braking and asymmetric thrust.

The steering system requirements have not been developed to a level of sophistication seen in skid control system design. The low-signal response (critical for high-speed regime) and large-signal response requirements (critical to low-speed maneuvers) are not well established. Due to the nature of directional control, which requires several inputs from the pilot, as against a simple brake pedal input for braking, the response cannot be easily assessed.

Recently, ground simulators have been developed which permit pilot evaluation of steering system adequacy and workload. A schematic of a ground handling simulator is shown in Fig. 2. These simulators are still not in wide-spread use. Comments such as "all simulators are alike" or "a moving-base simulator is better than a fixed-base simulator" clearly evade the basic issue: there is a need for extensive and accurate math models, such as in use on skid control simulators, and for adequate verification by pilot demonstration and flight test.

At this point it is perhaps timely to re-emphasize tire data needs for such work. Tire cornering and combined cornering and braking data are nearly nonexistent. Data needs for shimmy analysis also deserve mention. Nose gears have been frequently found to shimmy and steering valves have been often used to provide shimmy damping. Tire data must be available and new innovative approaches must be provided to resolve the shimmy problem. At present shimmy damping requirements often conflict with good high-speed directional control.

Procurement of the skid control system begins with the release of the specification, which outlines the typical system interfaces—hydraulic, electrical, and structural. Besires this, several system configuration requirements are imposed on the antiskid system manufacturer. Included in these may be requirements for: failure indication, touchdown and locked wheel protection, locked wheel protection—turning interface, parking brake system, and automatic spoiler deployment. Although these features are not a direct part of the braking force optimization system, careful consideration of these requirements is extremely important. The influence of some of these requirements can have a major effect on stopping performance, particularly under adverse runway conditions.

Skid control specification may also impose direct constraints on the type of system used. Recently, emphasis has been placed on providing more detailed accounting of tire, brake, and other associated component performance in the specification to assure harmonious operation of the skid control system.

Since the development of an antiskid system from scratch is both time consuming and costly, the selection of a system is usually limited to an existing system. Currently, operational aircraft use systems which cover three generations of antiskid development. Figure 3 shows simulator test results showing the improvement in system efficiency§ gained through system development as a function of available ground friction coefficient. Current third-generation systems provide high efficiency over a wide mu range, under ideal conditions.

One of the recent advances in brake control systems which deserves mention is the advent of the automatic braking system. The Boeing developed system concept provides: automatic application of brakes upon touchdown and a controlled deceleration to stop.

The following represent some of the payoffs of this concept: reduction of pilot work load, consistent early brake application, consistent operational stopping performance, smooth, comfortable operation, improved cornering capability, and reduced tire wear. This type of a system is now available on advanced B-737 and B-747 airplanes and is currently being developed for use on the B-727.

Additional performance gains can be obtained through both refinements to existing systems and the development of new concepts. In both areas, the airframe manufacturer is expected to play the key role since he is closely related to the

§System efficiency is defined as the ratio of minimum possible stopping distance at a particular available mu to the actual stopping distance.

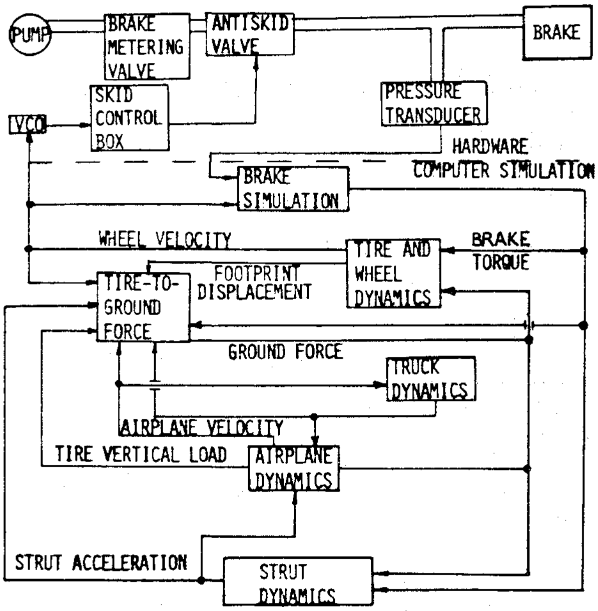

Fig. 4 Brake control system simulator block diagram.

system's operation, service problems, and is ultimately responsible for the safety of the aircraft. The antiskid supplier, on the other hand, is more closely related to the hardware and, with proper guidance from the airframe manufacturer, is in a better position to facilitate component improvement.

Laboratory System Development

Overall system performance depends to a great degree on the work done during the laboratory development. With the airplane, landing gear, and brake design essentially finalized, the skid control system components must be optimized to provide the desired performance.

The key element in optimizing performance of the skid control system is the simulator. The purpose of the simulator is to evaluate the system under all operating conditions. Figure 4 shows a block diagram of a typical simulator in use at Boeing. The simulation consists of an analog computer simulation of airplane and a hydraulic mockup. As much actual hardware as possible is used to insure complete representation and to minimize computer requirements. Simulated hardware is used initially, being replaced by prototype hardware as it becomes available.

The computer modeling includes: three-degree-of-freedom airplane, engine thrust characteristics, aerodynamic characteristics, landing gear dynamics, tire, wheel, and brake dynamics, ground force generation, truck pitch dynamics (if applicable) and brake torque with associated energy and velocity influences. Brake and tire dynamics form a major part of the simulation because of their basic influence on stopping performance.

The simulator is used throughout the design process. It must be used early in the process to avoid being locked into long-lead-time hardware. Thus, the simulator is used to screen system concepts as well as system components prior to vendor selection, thus, assuring the capability to meet the design requirements.

Once the hardware has been procured, system integration and optimization can begin. The test outline used during tuning and system development must be carefully developed to cover the entire anticipated regime of operation. This must include not only stabilized stops, but also step mu changes, wet runway operations, touchdown reactions, and environmental extremes. By means of the simulation, the stopping system is given a thorough preflight check for both dynamic stability and stopping performance. The critical control parameters of the antiskid control box are adjusted to insure an adequate stability margin, assuring "gear walk" free braking operation. Other dynamic influences such as truck pitch tendencies have to be assessed carefully and the necessary compensation provided in the electronics circuit.

The tuning for performance is a reiterative procedure. The component value changes and accompanying performance is assessed on the simulator. A significant gain must be verified by an actual airplane test. In addition, pilot opinion is often important. At times performance is good but the pilot may deem control rough from passenger acceptance point of view.

In order to assure reasonable correlation and detection of potential problems, it is essential that a credible simulator be developed. In addition to math modeling this requires use of best available data.

As a result of considerable IR&D and program activity, Boeing skid control simulators have achieved good credibility. These found extensive use on Adv-727, Adv 737, improved 747, and automatic brake system development work. Additional work is now underway for 727-300, YC-14, and 7X7 airplanes. Several new skid control concepts have also evolved for tomorrow. These systems will assure good wet runway performance and other benefits, such as improved cornering, increased tire, and brake life. Increasingly, there is talk of integrating the total stopping system, including thrust reverser.

Conclusions

a) Advances in stopping and directional control simulation techniques in recent years have permitted large improvements in stopping system performance.

b) Additional gains in steering and stopping performance require careful component optimization and integration into the total system. The environment under which operation is anticipated must be considered early in the design.

c) Additional tire data are needed to develop viable directional control systems for all-weather operation.

d) The traction capability of unprepared airfield deserves further study. Prepared asphalt and concrete runways need upgrading to improve traction during heavy rainfall.

e) To reduce impact of pilot technique on steering and brake systems, precise landing aids are needed. In addition, advisory information on available traction, cross-wind (magnitude and direction) is needed.

References

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