Boeing 737 Engine Gravel Protection

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The Boeing Model 737 Twinjet is certified for operation on gravel runways. The design and development of the nose gear gravel deflector with ground and flight test results is presented. A number of configurations were tested with the conclusion that satisfactory control of the nose tire gravel spray could be accomplished with only one type of gravel deflector. A description of the production nose gear gravel deflector is presented. Development of the engine vortex dissipator is presented. It is shown that the engine vortex dissipator must be controlled in both direction and momentum to prevent engine gravel ingestion.

Introduction

IT was decided in 1965 to proceed with development of a configuration which would allow the Boeing Model 737 airplane to operate from gravel runways. Design studies and analysis, combined with observation of airplanes already operating from gravel runways in Alaska, such as the F-27 and DC-4, let to the conclusion that the 737 airplane nose gear would require some type of deflector to prevent the nose tire gravel spray from damaging the wing mounted engines. It was believed at this time that engine vortex action would not cause undue gravel ingestion, but an engine vortex dissipator was found to be needed.

Airline operators have carried on successful operation from gravel runways since March 1969, with the Boeing Model 737 airplane, as shown in Fig. 1. The airplane incorporates a number of features to permit gravel runway operation. The design, development and testing, and testing of the nose gear gravel deflector is the primary subject of this paper. Highlights of the engine vortex dissipator parallel program are presented.

Development of a Nose Gear Gravel Deflector

The ground test rig for nose gear gravel deflector devices simulated operation of the full size nose wheels on a gravel test bed and determined the nose wheel gravel spray pattern. A rotating brush deflector design was selected based upon these test results and is shown in Fig. 2. Flight testing of this deflector was conducted in June and early July, 1968, at Fort Yukon and Kotzebue, Alaska, but this concept proved unsatisfactory in that the amount of gravel which the engines ingested from the nose wheel spray would cause excessive foreign object damage to the engine compressor blades. It was also concluded that the engines would require a vortex dissipation system for airplane speeds below approximately 15 knots.

An intensive design, development and testing program was initiated in July 1968. Two gravel runways were constructed at the Grant County Airport, Moses Lake, Washington. The small strip was 200 ft long, 8 ft wide, and 4 in. thick, laid on a concrete taxi way. The larger strip was 1000 ft long, 75 ft wide, and 6 in. thick, laid on the thin asphalt stabilized gravel shoulder on the east side of runway 32. The test airplane was equipped with engine inlet screens. Cameras mounted on the airplane obtained motion pictures of the nose gear, main gear and engine inlet, at framing rates up to 1000 frames/sec. A camera was also mounted below the left-hand engine cowl with a mirror to obtain motion pictures looking up into the engine inlet. Observers were stationed during taxi runs in the lower forward baggage compartment to make direct observation of the nose gear and the right-hand main gear and engine. During the total nose gear, gravel-runway flight test program, over 80,000 ft of movie film was used, and approximately 120 hrs of taxi and flight time was accumulated.

The initial taxi runs were conducted on the small narrow gravel test strip with one main gear only running on gravel and then with the nose gear only running on gravel. These tests proved that the main gear was not a source of gravel ingestion for the engines. Taxi, takeoff, and landing tests were conducted on the 1000-ft strip. Airplane start-up and final stopping were done on the concrete runway, which was kept clean of any gravel to eliminate the possibility of engine vortex action masking the nose gear deflector results. The

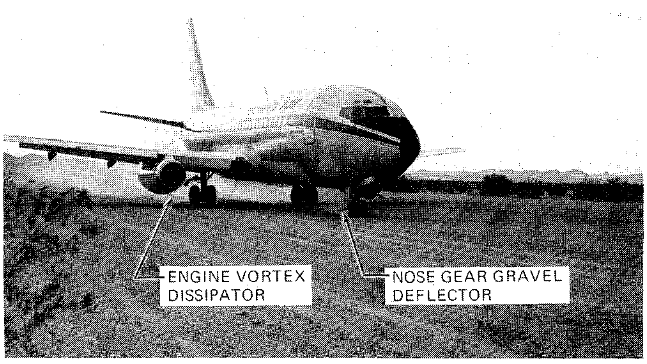

Fig. 1 A Boeing 737 airplane operating off a gravel runway.

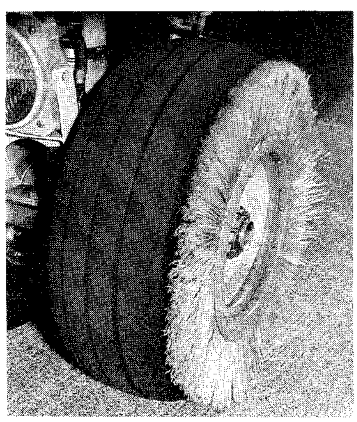

Fig. 2 Rotating brush type gravel deflector for nose wheel.

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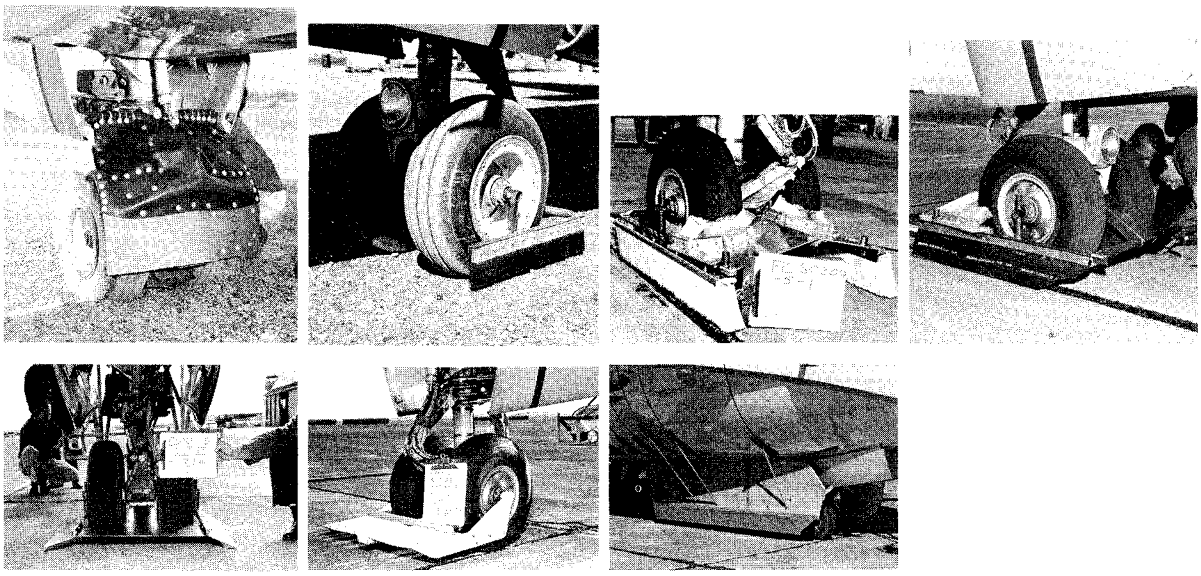

Fig. 3 Some of the gravel deflector concepts tested: a) fender; b) soft brush; c) brush; d) rubber side deflector; e) canted metal deflector; f) metal chute; g) body strake.

engines at this time were not fitted with vortex dissipator booms.

Design and fabrication work on a variety of nose wheel gravel spray deflectors was conducted simultaneously with preparation of the test airplane and building of the gravel test strips. Design ideas were considered initially only on the basis of accomplishing the primary objective: prevention of foreign object damage to the engine beyond that sustained on surfaced runways. Considerations such as how to retract the gravel deflector were not used to judge the various prototype designs. A number of project and staff engineering groups within Boeing were solicited to provide ideas for nose gear designs which could be fabricated and tested either in the laboratory or on the test airplane. Design studies were also made of various engine inlet devices such as retractable screens, protected air inlets, and gravel rock traps for the engine inlet cowls. It was concluded that the problems of engine thrust loss, anti-icing, compressor inlet pressure distribution and the potential ingestion of mechanism located in the inlet, combined with the extensive retesting of the engine in-flight performance characteristics, would make the engine inlet design approach undesirable.

During July and August, 1968, thirty distinct nose gear gravel deflector configurations were designed. One device consisting of air jets to control gravel spray was tested in the laboratory and discarded because of the quantity of air required to accomplish satisfactory gravel deflection. Twenty-two configurations were taxi- or flight-tested during the development program which ended September 5, 1968. Figure 3 shows seven of them. The configuration chosen consisted of a horizontal deflector with a smooth steel bottom 42 in. wide and 48 in. long, located 3.5 in. above the runway surface and fitted closely around the nose wheels. A final test of the prototype design was made with high speed taxi runs through $\frac{1}{2}$ in. of runway water to insure that the deflector water spray characteristics were not detrimental to engine operation. Also a final test of the deflector design

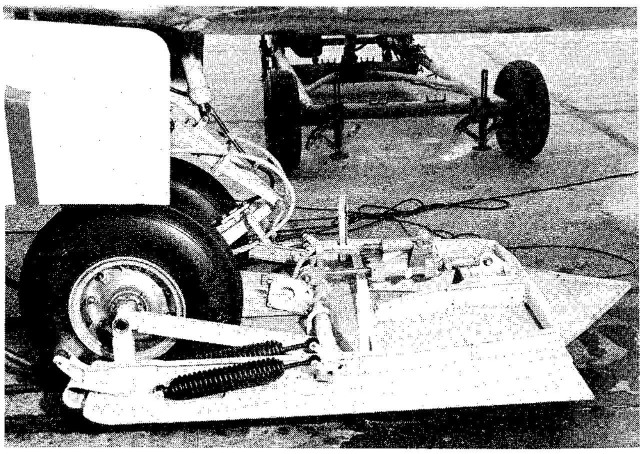

Fig. 4b Production deflector, left hand side view.

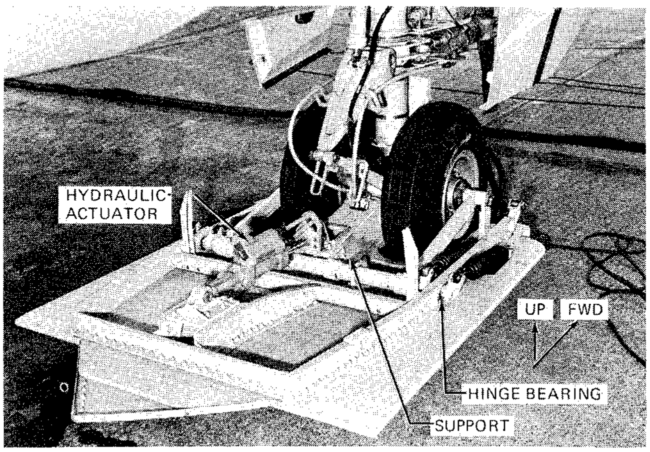

Fig. 4a Production deflector, $\frac{1}{4}$ rear view.

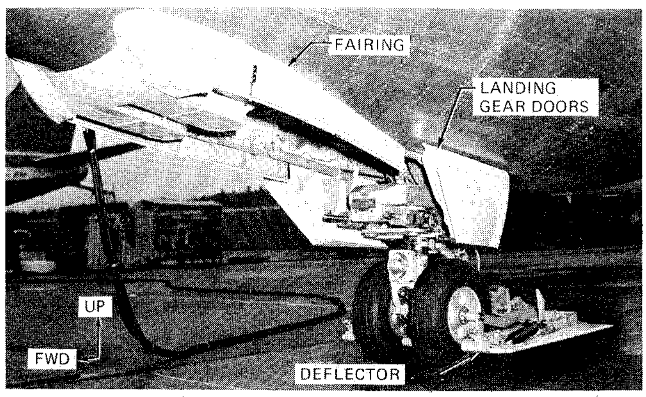

Fig. 4c Production deflector, $\frac{1}{4}$ front view.

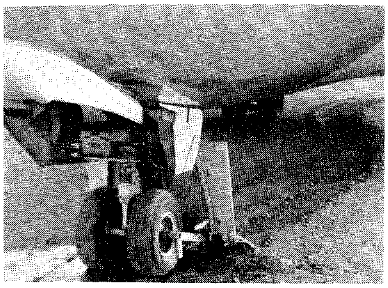

Fig. 5 Early production deflector failure.

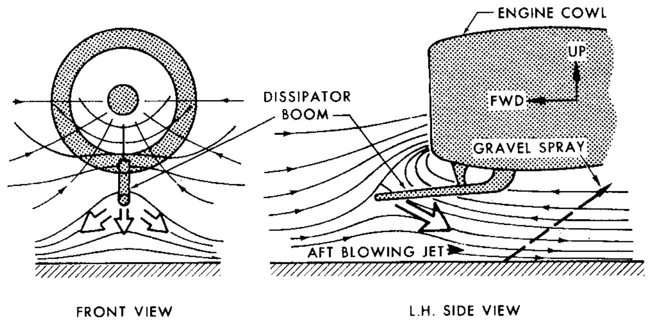

Fig. 7 Engine vortex dissipator, aft blowing.

was made on a full length gravel runway at Annette Island, Alaska, with a number of flight operations to provide sufficient data sampling. The production model is shown in Fig. 4 and is discussed in the next section.

The conclusions drawn from this development work were that a nose gear gravel deflector should: deflect gravel spray only downward; impart a minimum amount of energy to the gravel; deflect the gravel spray low enough so that ricochetes from the airplane surfaces and, in particular, from the main gear are minimized; and should not contact the runway surface. In support of these conclusions, it was found that: deflector designs which contained vertical fences or flaps caused lateral dispersion of gravel; vertical fences or flaps imparted airplane motion energy to the gravel, which allowed gravel spray to lead the airplane instead of falling behind it; a portion of the gravel spray which is ingested by the engines consisted of ricochetes from the airplane itself; and any device, regardless of its stiffness, created a gravel spray when it contacted the runway surface.

Production Deflector Design

The production deflector (Fig. 4) is made of marine plywood covered with hard stainless steel on the lower surface. Aluminum and steel members support it from the nose gear axle. It rotates on a hinge and is driven by means of a hydraulic actuator. During operation of the nose landing gear, hydraulic fluid from the nose landing gear actuator up or down supply is fed to the deflector actuator. The deflector is hydraulically programed with respect to the nose gear motion, so that it maintains a nose-up attitude during retraction and extension of the landing gear. The deflector, with the landing gear retracted, lies flat against a fairing located around the nose wheel well; and the forward portion of the basic airplane nose landing gear doors is replaced by the gravel deflector. The springs on the deflector assist in obtaining free fall of the nose gear and in maintaining a nose-up attitude of the deflector. The springs also hold the deflector in its proper ground attitude when the gear is down and hydraulic power is off.

The production design was modified after it had been in airline servide in order to revise the deflector actuator control system. The original control system consisted of a mechanical push-pull cable unit which sensed landing gear position and operated a servo valve on the deflector hydraulic actuator. The revised control system eliminates the mechanical cable and servo valve and programs the deflector actuator by means of a hydraulic flow limiter. The mechanical control system was subject to jamming due to moisture freezing. This would then incorrectly program the deflector to a vertical position for landing. Figure 5 shows the results of landing with the deflector in a vertical position. There was severe damage to the deflector, but only very minor damage to the airplane and engines.

The production design was begun in September 1968; delivery of an airplane with an FAA certified functionally operating deflector was made to Wien Consolidated Airlines on December 6, 1968. Final FAA certification for gravel operation was obtained in February 1969, following 25 functional and reliability flight operations made on a gravel runway at Lake Havasu, Arizona. The nose gear gravel deflector imposes no limitations upon the 737 airplane operation other than a reduced landing gear placard speed and a small increase in cruise drag.

Vortex Dissipator

A design development and testing program to determine a suitable engine vortex dissipator configuration was carried on concurrently with the nose gear gravel deflector program. A concept of blowing air down and forward from a nozzle on the engine cowl in order to dissipate the inlet vortex was adopted. Engine ground rig tests were followed by airplane testing on the Moses Lake gravel strip. These tests indicated that forward blowing with sufficient mass flow to control the vortex in crosswinds would not be feasible, in that gravel was disturbed on the runway surface and then blown up and forward into the engine inlet stream. Figure 6 shows the forward blowing concept.

Design and testing was then begun on an aft blowing concept which would dissipate the vortex but allow any disturbed gravel to be thrown up aft of the engine inlet. Engine ground rig tests, separate gravel surface spray tests, and wind-tunnel tests of the engine compressor inlet face pressure distribution were conducted. A final aft blowing dissipator boom with three nozzles was found to be satisfactory. The center nozzle is 0.62 in. in diameter and the two side nozzle

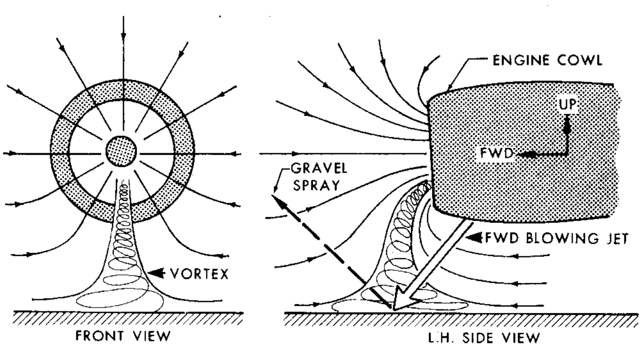

Fig. 6 Engine vortex dissipator, forward blowing.

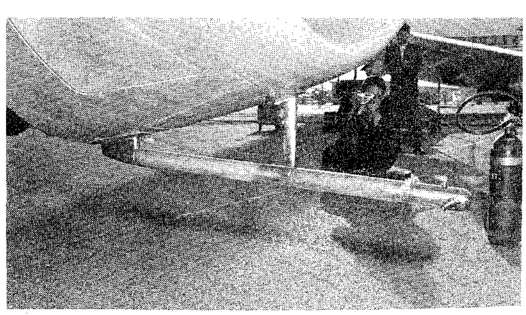

Fig. 8 Engine vortex dissipator boom, 1.4 front view.

are 0.53 in. in diameter; air is supplied from the engine 13th-stage bleed with 15-psig nozzle pressure at idle engine power and regulated to 55 psig at higher engine powers. Figures 7 and 8 show the final aft blowing concept.

The dedicated efforts of many people within The Boeing Company, combined with assistance and understanding from the airlines involved, were the ingredients which made the entire program successful.

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Flight Investigation of the Influence of Turbulence on Lateral-Directional Flying Qualities

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Flight evaluations using a variable stability airplane were made to determine the independent and interacting effects of simulated turbulence disturbances and lateral-directional dynamics on flying qualities associated with a precision heading control task. Turbulence was described in terms of rms roll and yaw disturbance magnitude, correlation between roll and yaw disturbances, and the bandwidth of the turbulence power spectrum. Variations in dynamics included roll damping, directional stability, and Dutch roll damping. Trends in pilot rating obtained in the test program with variations in turbulence disturbances and airplane dynamics are explained in terms of measures of precision of task performance, pilot control workload, and pilot compensatory behavior derived from time histories of the flight evaluations.

Nomenclature

L = rolling moment or roll angular acceleration
L_{ug},L_{vg},L_{wg} = roll angular acceleration due to u_g,v_g,w_g
L_{β_g} = derivative of roll acceleration with respect to sideslip disturbance, $(1/I_x)$, $\partial L/\partial_{\beta_g}$
L_{pg} = derivative of roll acceleration with roll gust disturbance, $1/I_x \partial L/\partial_{pg}$
L'_i = Primed roll acceleration derivative $L_i + (I_{xz}/I_x)N_i/1 - (I_x{}^2/I_xI_z)$
N = yawing moment or yaw angular acceleration
N_{ug},N_{vg},N_{wg} = yaw angular acceleration due to u_g,v_g,w_g
N_{β_g} = derivative of yaw acceleration with respect to sideslip disturbance, $(1/I_z)$, $\partial N/\partial_{\beta_g}$
N_i = primed yaw acceleration derivative, $N_i + (I_{xz}/I_z)L_i/1 - (I_{xz}{}^2/I_xI_z)$
N_{L^i},N_{N^i} = transfer function numerators relating response i to roll and yaw disturbances
R_e = real part of a complex number
T_R = roll subsidence mode time constant
T_{v1},T_{w1} = time constants associated with the corner frequencies ω_{v1} and ω_{w1} of the disturbance spectra
V_0/L = parameter defining the corner frequency of the turbulence spectrum; V_0 = true airspeed, L = integral scale of turbulence
Y = lateral acceleration
Y_{ug},Y_{vg},Y_{wg} = lateral acceleration due to u_g,v_g,w_g
b = wing span
c = wing chord
g = acceleration due to gravity
p = roll rate
r = yaw rate
u,v,w = longitudinal, lateral, and vertical velocity perturbations
u_g,v_g,w_g = longitudinal, lateral, and vertical gust velocities
β = sideslip angle
Δ' = characteristic equation for closed loop manual control
δa_s = lateral stick deflection or force
δr_p = rudder pedal deflection or force
σ_i = root mean square of the variable i
Φ_i = power spectral density of the variable i
φ = bank angle
Ψ = heading
ω_d,ζ_d = dutch roll natural frequency and damping ratio
ω_{v1},ω_{w1} = bandwidth of the lateral and vertical gust disturbance spectra
$| \ |$ = absolute value
$(\ )^*$ = complex conjugate of ( )

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Introduction

TURBULENCE, whether encountered in VFR cruise flight or under a precisely controlled IFR terminal area maneuver, whether encountered as a pilot or as a passenger, can be a highly disconcerting, discomforting, and a potentially dangerous experience. And yet, in the history of study of airplane flying qualities, a conspicuously small amount of attention has been paid, either theoretically or experimentally, to the effects of atmospheric turbulence on the pilot's capability to control the airplane. Certainly there has been some degree of awareness that the airplane's turbulence response characteristics play a part in determining its over all handling characteristics. NACA Report No. 1 titled "Report on Behavior of Aeroplanes in Gusts" is an indication of the early interest in the general subject. Ample evidence is available from pilot commentary collected during operational use, airplane flight test programs, variable stability airplane programs, and the like, of the deleterious effects of turbulence on the pilot's ability to control the airplane satisfactorily. However, to this date, no systematic study has been made to achieve a fundamental understanding of the relationship of turbulence to flying qualities.