have dynamic stall behavior similar to 8° amplitude data for $\alpha_0 = 27°$, rather than for $\alpha_0 = 24°$. (That gives minimum angles of attack of 18° and 19° for $\Delta\alpha = 6°$ and $\Delta\alpha = 8°$, respectively.) It appears that our predictions using applicable static data (Fig. 4) is superior to their "repredictions" of the dynamic data (Fig. 13).

In conclusions, it appears that dynamic stall is a phenomenon that is very difficult to simulate in subscale tests in ground facilities because of possible pitch rate induced changes of the stall type. A change of stall type can also occur locally due to variation of wind-tunnel wall and support interference effects with oscillatory frequency. This local effect will be a problem mainly in tests that use one row of pressure orifices to determine the two-dimensional airfoil characteristics. Even if truly two-dimensional results can be obtained, their application is questionable, since they do not include the ventilation of the separated flow region provided by the various types of vortices always present in the "real life" three-dimensional flowfield.

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Reduction of Tractor-Trailer Cross-Wind Response

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IT has long been recognized that automobiles towing trailers are highly responsive to cross-wind disturbances. With the increasing numbers of travel trailers and camper trailers on the highways it is necessary to examine this problem to determine the effect of various parameters on the gust response.

For the purposes of this analysis the motion of an articulated automotive vehicle can be described by the three-degrees-of-freedom of lateral velocity (represented by the side-slip angle β), turn rate r, and the angle between the tractor and the trailer θ (Fig. 1). The possibility of both the tractor and the trailer rolling on the suspension is not included, thereby eliminating any effects of the vertical gradient of the cross-wind gust. Even though the vertical gradients of the wind play a large role in gust response[1]; the complication of two additional degrees of freedom makes their inclusion undesirable at this time.

The linearized equations of motion are obtained using the standard small disturbance approximations. The tire forces and moments enter the equations through the chassis stability derivatives which depend on the properties of the pneumatic tires (cornering power and aligning torque) and the mass distribution of the vehicle. The only longitudinal force which appears in the linearized equations of motion is evaluated in the reference state. Thus, if the vehicle is operated at constant speed, the longitudinal component of the wind will

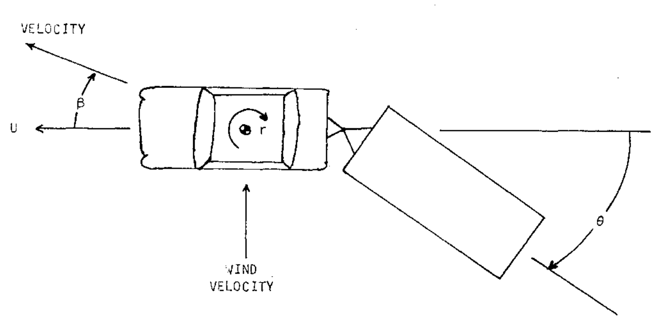

Fig. 1 Vehicle coordinates.

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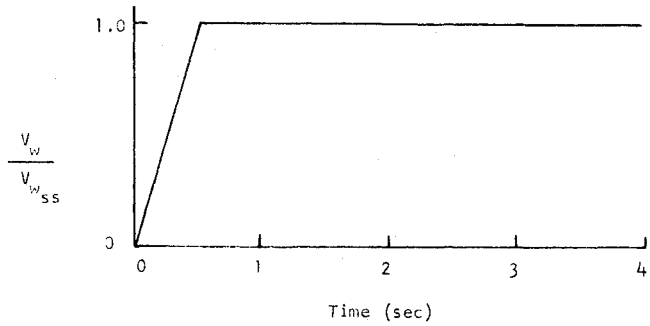

Fig. 2 Cross-wind gust disturbance.

have no effect on the lateral dynamics and only the cross-wind components of the gust need be considered.

The cross-wind velocity produces an effective gust side-slip angle. Likewise the horizontal gradient of the cross-wind produces an apparent angular velocity or turn rate. By transferring to a moving coordinate system attached to the vehicle the horizontal gradient of the wind is expressed as the time derivative of the gust side-slip angle. In addition to the aerodynamic forces produced by side-slip and turn rate, the cambering of the vehicle because of the angle θ also produces aerodynamic forces and moments. The aerodynamic forces are introduced to the equations of motion through standard aerodynamic stability derivatives. It is important to note that the wind velocity at the trailer is not the same as the wind velocity at the tractor since the vehicle must travel a finite distance between the time the tractor encounters a gust and the time the trailer encounters the same gust.

Two basic vehicles were chosen for this study, a snub-nose tractor-trailer truck and a sedan towing a medium sized travel trailer. Both vehicles were assumed to be operating at a constant forward speed of 60 mph with the steering fixed. The wind gust input used is shown in Fig. 2.

Figure 3 shows the response of the truck to the gust. The response is small, a 15 mph cross-wind producing a steady-state turn rate of less than 0.5°/sec. The steady-state turn rate is negative, that is the vehicle turns into the wind, a basically stable response. The dashed line shows the response of the tractor towing a streamlined trailer. The trailer was streamlined by rounding corners and by adding an extended "beaver tail" to the rear. This reduced trailer drag by 20%. It is seen that the increase in cross-wind response which results is quite small and a small penalty to pay for a large decrease in drag.

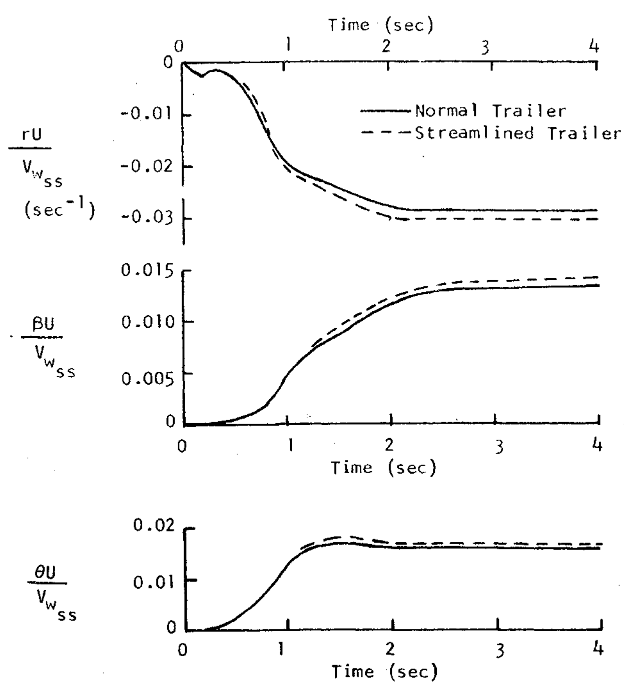

Fig. 3 Response of tractor-trailer truck.

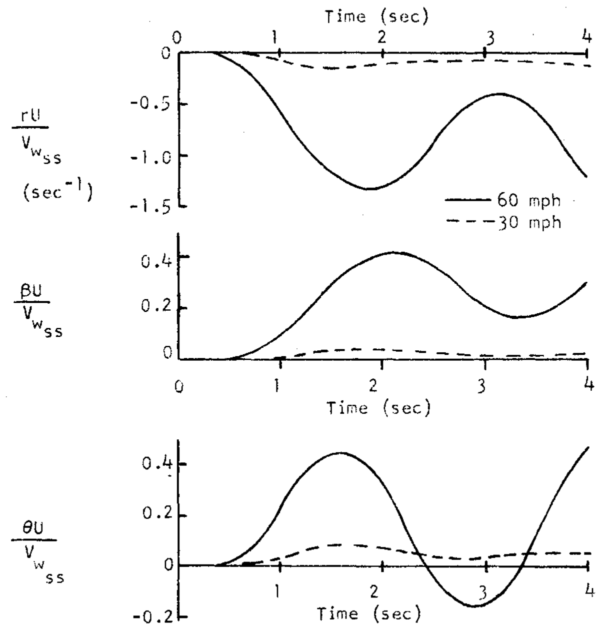

Fig. 4 Response of automobile towing travel trailer.

A lightly damped, stable, oscillatory mode is excited in the car-trailer system by the gust (Fig. 4). If the gust response were due entirely to the aerodynamics, doubling the speed should cause the normalized response to be multiplied by four. Figure 4 shows that the response is actually increased by a factor of ten when the speed is doubled. Thus there is an important interaction between the aerodynamics and the chassis in the vehicle gust response.

In order to see if the gust response might be reduced by mechanical means calculations were made for the car-trailer system with a spring and a damper placed between the car and the trailer. The spring rate was 100 ft-lb/deg and the damper rate was 100 ft-lb-sec/deg. The results of these calculations are shown in Fig. 5. The damper has little effect on the amplitude of the response but does decrease the frequency. The spring, however, more than halves the amplitude of the response. It is interesting to note that the "compensating hitch" normally used when towing large trailers with an automobile provides a springing action between the car and trailer.

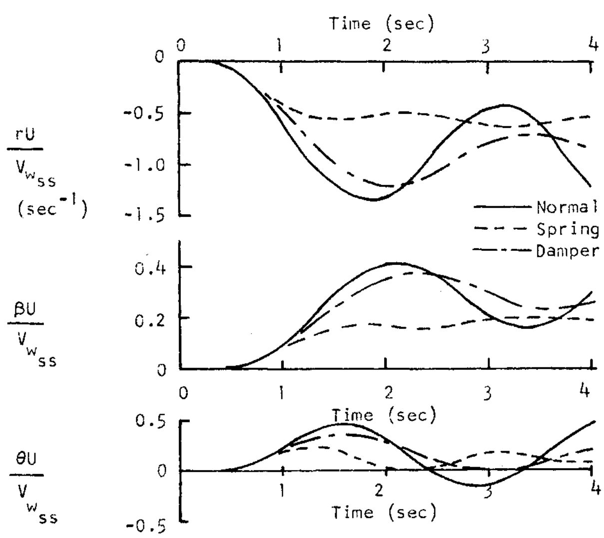

Fig. 5 Mechanical reduction of gust response.

There is no particular advantage to using both a spring and a damper.

The dominant aerodynamic parameters in the gust response are the trailer yawing moments produced by β and θ with the side-slip term being the more important of the two. The other aerodynamic terms have only a small effect on the gust response.

In summary, certain characteristics of the cross-wind response of tractor-trailer type vehicles were obtained on the basis of a simplified model. Tractor-trailer vehicles apparently possess an inherent weathercock stability as opposed to single automotive vehicles which are almost invariably unstable in a cross wind. Gust response can be reduced by reducing the trailer aerodynamic yawing moments or by using a spring between the tractor and the trailer. These are two possible avenues for further research.

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Advantage of Testing Aircraft Rotor Models with Sharply Deflected Wakes in Water

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IT is clear that if a model of a helicopter is tested in a wind tunnel, Reynolds number scaling must generally be abandoned. On the other hand, if the size of the model is increased, Reynolds number scaling will be improved but wall interference may become intolerable. It will be shown here that testing a small model in a water tunnel instead of testing a somewhat larger model in a wind tunnel provides a Reynolds number that is large enough so that overall rotor lift characteristics are simulated correctly while, at the same time, wall interference is considerably less severe than in a wind tunnel. Furthermore, there exists a bubble technique[1,2] that can be used to render tip vortices visible in water, and there is no comparable technique for air.

Consider the problem of Reynolds number scaling. In the first place, the kinematic viscosity of water is about twenty times smaller than that of air and this means that small models can operate in a water tunnel at Reynolds numbers for which a considerably larger model is required in air. But of even more importance is the fact that below the stall, blade lifting characteristics are virtually independent of Reynolds number, and Reynolds number serves mainly to limit the maximum lift that can be achieved at any radial section. This means that a full-scale Reynolds number is not required to obtain meaningful results. For a helicopter rotor operating at a full-scale Reynolds number all sections are likely to be operating below the stall, while for operation at model-scale some sections may have stalled out. However, if at model-scale only the sections near the hub are stalled, the effect on the overall lift will be small, since inboard sections contribute very little to the overall lift whether they are stalled or not. Consequently, if model tests are carried out at a Reynolds number for which only inboard sections are stalled, such tests should still give good predictions of full-scale total lift characteristics.

The relative insensitivity of rotor total-lift characteristics to Reynolds number is illustrated in Table 1 where simple strip theory has been applied at two widely different Reynolds numbers to a hovering 48 ft diam UH-1D rotor whose blade section is an NACA 0012 airfoil with a 21 in. chord. The twist in the rotor blade is 0.454°/ft and the tip speed is approximately 800 fps.‡ The collective pitch angle of the rotor is 14.1°, which corresponds to the setting for a total lift of 7000 lb. The blade was divided into ten equal strips and the sectional lift coefficients were obtained from the data presented in Ref. 3 for the higher Reynolds numbers and by interpolating the data, also given in Ref. 3, for the 0009, 0015 and 0018 airfoils for the lower Reynolds numbers. The total lift is calculated and it can be seen that the lift for a Reynolds number (based on blade chord and tip speed) of 7.9×10^4 differs from the lift at a Reynolds number of 9.1×10^4 by less than 2% despite the fact that inboard sections of the rotor are stalled at the smaller Reynolds number.

Having shown that Reynolds number scaling is of secondary importance for rotor tests provided the model and full-scale Reynolds numbers are not too disparate, it will now be shown that rotor wake dissipation characteristics at model-scale are such that the wall upon which the wake impinges (which is the critical one for hover) can be located considerably closer to the model in relation to its size in a water tunnel than in a wind tunnel before wall interference creates unacceptable distortion in the data.

It will be assumed that the mechanism that controls the breakdown of the wake as a whole in either water or air is laminar dissipation, in which case the wake can be simulated by an incompressible laminar circular jet. Then, according to Schlichting,[4] p. 218, the axial velocity u varies with distance downstream x as

$$u \sim J/\rho\nu x \tag{1}$$

where J is the jet momentum, ρ is mass density, ν is kinematic viscosity. In simulating the helicopter rotor wake by a jet, the analog of the jet momentum is the total load on the rotor, so that if A represents the area of the disc and p the disc loading

$$J = pA \tag{2}$$

The volume of flow Q is related to the axial velocity according to the order of magnitude relationship

$$Q \sim uA \tag{3}$$

and, from the solution given in Schlichting

$$Q \sim \nu x \tag{4}$$

Upon eliminating J, Q and u from these four equations there results the following expression for x

$$x \sim (A/\nu)(p/\rho)^{1/2} \tag{5}$$

If x is now interpreted as the distance below the rotor disc beyond which no axial flow is discernable, then measurements for various disc loadings should show that this distance varies as the square root of p. Indeed, measurements using tufts in the Oceanics water tunnel over Reynolds numbers ranging from 2.3×10^4 to 9.1×10^4 confirm this variation[5] and yield the constant of proportionality. The final formula then becomes

$$x = 0.000232\ (A/\nu)(p/\rho)^{1/2} \tag{6}$$

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‡ Although compressibility effects are likely to be important for determining true total rotor lift at this speed, for simplicity, incompressible flow has been assumed in making the present Reynolds number comparisons.