ROUGHNESS CRITERIA AND THE RELATIONSHIPS BETWEEN SURFACE ROUGHNESS AND FLOW NOISE

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ABSTRACT

Roughness criteria are usually given for the surfaces of structures to prevent premature structural failure, added drag, and added flow noise. Structural roughness criteria usually deal only with long wavelength roughness, or waviness, which is specified in terms of clearance under a batten of a particular length. Drag roughness criteria usually deal only with the short wavelength roughness as measured by a profile meter. Flow noise roughness criteria, however, must include both the long and short wavelength components of the roughness and, in the case of water, separate criteria are needed for boundary layer turbulence and cavitation induced noise. A more unified description of roughness and roughness criteria is given in terms of its wavenumber spectrum. Hydraulically smooth surfaces are believed to have no roughness related component of drag or turbulence induced flow noise. In water, for instance, the surface is considered to be hydraulically smooth if the roughness height in inches is less than about 0.01 divided by the free stream velocity in knots. The expected increase in turbulence induced flow noise in water and in air as a function of roughness and flow speed is then determined from available data on local skin friction.

The surface of any real body contains deviations from the average contour that are described in terms of roughness and waviness. These deviations are of interest in the field of strength, fatigue, friction, wear, drag, and noise generation. The strength of pressure vessels, for instance, depends on out-of-roundness and fatigue strength can depend on initial roughness or cracks in the surface. Friction and wear are influenced by the fine grain roughness, bearing length, etc. The drag of bodies moving in fluids is known to depend on the roughness. Flow noise generated by bodies moving in fluids is also known to be dependent on roughness and waviness. This noise and its dependence on the properties of the waviness and roughness of the body are the main concern of this paper.

Surface flaws with wavelengths greater than about 1/32 inches are considered to be waviness. Those with wavelength less than this are considered to be roughness. Waviness is conventionally described in terms of clearance under a batten of a particular span, say 1/8 inch in 4 inches. This peak-to-valley distance is defined here as $2h_o$ and the wavelength or span as λ. If one plots wave amplitude h_o as a function of reciprocal wavelength $1/\lambda$, points of constant ratio $\lambda/2h_o$ lie on a line having a -6 db/octave slope as shown in Slide 1. This line moves down 6 db each time the $\lambda/2h_o$ ratio is doubled and up 6 db each time it is cut in half. These are specifications of a line spectrum.

Roughness is conventionally described in terms of average height or rms height and is measured using one of a number of available profile measuring devices. These devices move over the surface with a stylus and produce an electrical signal proportional to the transverse displacement of the surface. This signal can be read directly on an averaging or on an rms meter to give readings of average or rms roughness height. This signal can also be recorded or traced to give a profile of the surface itself when properly calibrated and normalized in terms of the velocity of travel over the surface. A typical traversing speed of 0.1 in/sec over roughness wavelengths from 10^{-4} to 10^{-2} inches gives frequencies between 10 and 1000 Hz. This trace is not unlike a trace of sound pressure as a function of time and can be analyzed in the same way. We are seldom satisfied with just the rms amplitude of such a signal. Acoustic pressures are usually described in terms of their spectral density because their frequency content is of interest. Indeed we are interested in the "frequency" content of the roughness also. Such an idealized roughness spectral density is also shown on the slide. Since the spectral density is the square of the amplitude per cycle/inch bandwidth, the slope of the constant $\lambda/2h_o$ lines are -9 db/octave instead of the -6 db/octave for the waviness points which are essentially line components which have not been divided by the bandwidth. The levels of these lines are a measure of the peakiness of the roughness, i.e., the lower the $\lambda/2h_o$ ratio is, the peakier the roughness is. A value of 2 indicates a double amplitude equal to half a wavelength which is roughly what one would obtain for closely packed sand grains glued to a flat surface.

It should be noted that the frequency response of the profile meter electronics, the radius of the stylus tip of the profile meter, the length of the sample, and the "wheelbase" of the profile meter all limit the frequency limits of the spectra that can be measured. The frequency calibration of the profile meter can be used to correct for deficiencies in the electronics but the others are inherent limitations for a particular instrument.

One can obtain the rms roughness from the spectral density in the usual way by integration or using the bandwidth at the 3 db down points. Typically a hand ground surface ranges from about 250 to 1000 microinches rms and a highly polished surface is in the few microinch range. Turbulence stimulator pins used on models are typically about 1/8 inch in diameter and 0.035 inch high.

In order to determine the inception of cavitation on roughnesses on the wall of an underwater body, one must know the local pressure around the roughness relative to the vapor pressure of water. Cavitation can occur on roughness with a low $\lambda/2h_o$ ratio and large enough to protrude well out into the boundary layer. The important velocity to be used in the cavitation number and Reynolds number is the local velocity at the height of the roughness. Cavitation inception speeds for rough hydrodynamic bodies have been computed by Borden (6th Naval Hydrodynamics Symposium, Vol. 1, Sep 28 - Oct 4, 1966, Washington, D.C.). As expected, sharp roughnesses are more prone (by several knots) to cavitate than rounded ones. On typical streamlined bodies at reasonable depths, the roughness must be almost sticking out of the boundary layer before it will cavitate. At shallow depths, on blunt bodies, or at high speeds cavitation can occur at relatively small roughnesses. For predicting cavitation inception, individual roughnesses are best described by their size and shape rather than in spectral form but if their size and shape are randomly distributed over an extended area, a spectral description is appropriate. In this case, as in fatigue problems, the statistics of occurrence of peak values are also important. It is assumed, of course, that if cavitation is present, significant noise is produced.

Waviness with $\lambda/2h_o$ ratio of some 32 or more is not expected to enhance the flow noise from a body. Such a gradual change in contour would alternately slightly increase and then slightly decrease the pressure gradient along the body and have a slight net effect on the boundary layer. If $\lambda/2h_o$ decreased from this, however, separation of the flow will eventually occur behind the peaks and increased turbulence, drag, and boundary layer pressure fluctuations will result.

Roughness is known to increase the drag or local skin friction if it exceeds the so called hydraulically smooth condition. In Schlichting's 4th edition of Boundary Layer Theory, plots are given of local skin friction coefficient as a function of Reynolds number and roughness height ratio. Schlichting also gives an expression for the admissible roughness to be $h_{adm} \leq 100\nu/U$ where ν is the kinematic viscosity and U is the free stream velocity. One should note that this expression is independent of distance x along the body but holds only for Reynolds number, $R_x = xU/\nu$, between the values of 10^7 and 10^9. Above 10^9 the admissible roughness height is slightly lower. A value of $3(10^6)$ is considered a typical value for transition from laminar to turbulent flow.

For water at typical temperatures and the velocity in knots, the admissible rms roughness height in inches is given simply by h_{adm} (inches) ≤ 0.01/U (knots). For air at typical conditions and the velocity in feet per second, the expression becomes h_{adm} (inches) ≤ 0.2/U (ft/sec). If one now makes the assumption that the rms pressure fluctuations at the wall are proportional to the local skin friction coefficient (which in turn is proportional to the local shear stress at the wall), one can then determine increases in rms wall pressure for roughness above the hydraulically smooth value. This has been done on Slide 2. For approximately 10 knots in water or 200 ft/sec in air, a surface is considered hydraulically smooth if it has an rms roughness less than 1000 microinches. For a roughness some ten times this value, an increase of about 3 db in the rms pressure over the smooth surface value is to be expected. Curves for other speeds are also shown. Since it is expected that fine grain roughness influences the high frequency pressures and large grain roughness and waviness influences the low frequency pressure, it is essential that we know the frequency spectrum of the roughness before we can expect to predict the influence of roughness on the frequency spectrum of the fluctuating pressures at the wall. Considering the assumptions made for the slide, an accuracy better than a db or an octave in roughness or velocity is not likely.

It is obvious then that for flow noise work related to roughness, we need a spectral description of surface roughness and waviness. A spectral density using reciprocal wavelength or wave number is proposed here for such a unified description. Profile meters with a wide frequency response are needed for this. The low frequency response especially, needs to be extended several decades. The line component specification is not really appropriate because very few surfaces have a sinusoidal character but have broad-band spectral content. This wavenumber spectrum of the surface roughness seems especially appropriate for convolving with the wavenumber spectrum of the convecting boundary layer pressure fluctuations.

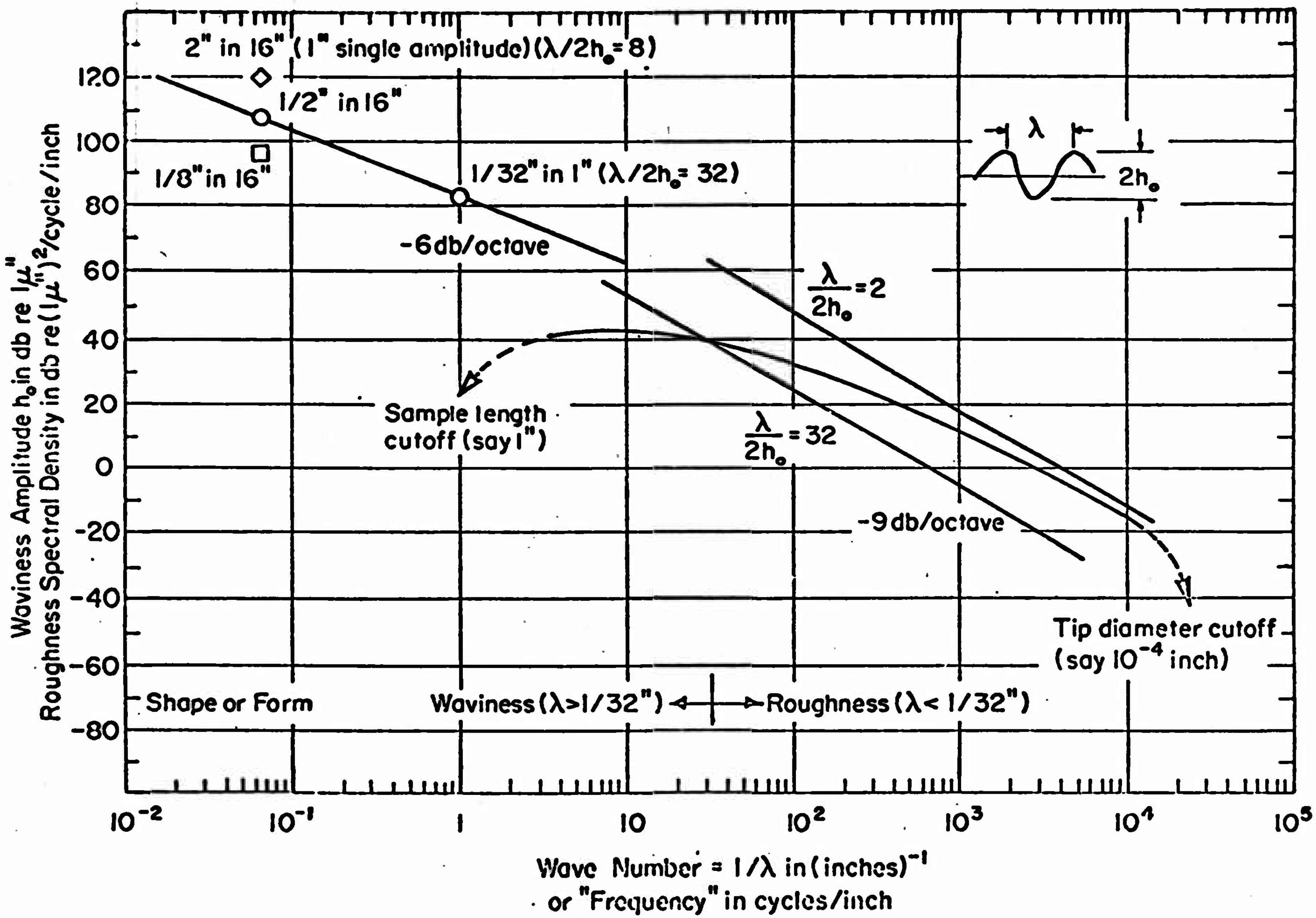
2" in 16" (1" single amplitude) (λ/2h₀ = 8)
1/2" in 16"
1/8" in 16"
1/32" in 1" (λ/2h₀ = 32)
-6 db/octave
λ/2h₀ = 2
λ/2h₀ = 32
-9 db/octave
Sample length cutoff (say 1")
Tip diameter cutoff (say 10⁻⁴ inch)
λ
2h₀
Shape or Form
Waviness (λ>1/32")
Roughness (λ< 1/32")
120
100
80
60
40
20
0
-20
-40
-60
-80
10⁻²
10⁻¹
1
10
10²
10³
10⁴
10⁵
Waviness Amplitude h₀ in db re 1μ"
Roughness Spectral Density in db re (1μ")²/cycle/inch
Wave Number = 1/λ in (inches)⁻¹
or "Frequency" in cycles/inch

Figure 1

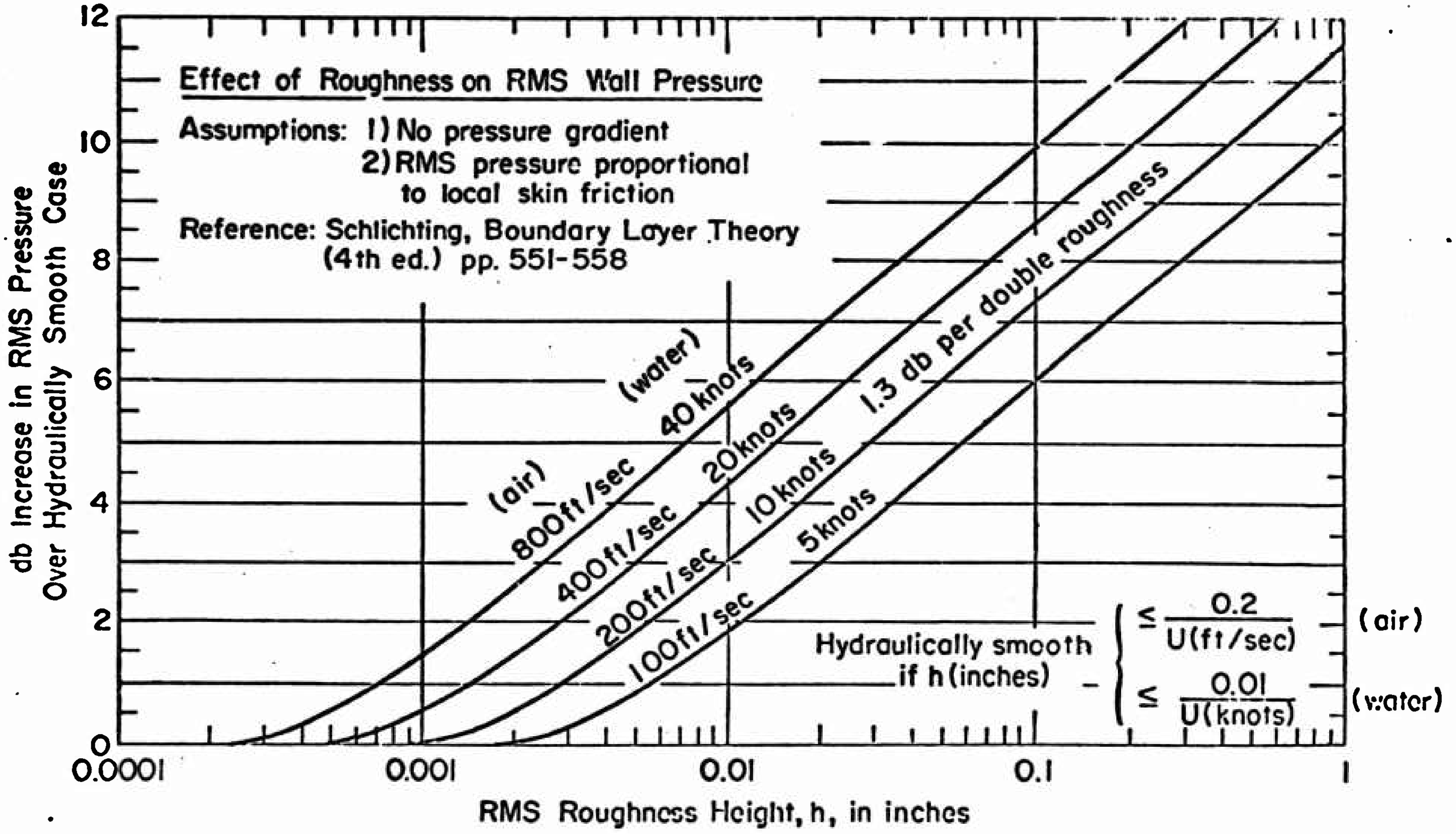
Effect of Roughness on RMS Wall Pressure
Assumptions: 1) No pressure gradient
2) RMS pressure proportional to local skin friction
Reference: Schlichting, Boundary Layer Theory (4th ed.) pp. 551-558
(water)
40 knots
20 knots
10 knots
5 knots
(air)
800 ft/sec
400 ft/sec
200 ft/sec
100 ft/sec
1.3 db per double roughness
Hydraulically smooth if h (inches)
≤ 0.2 / U(ft/sec) (air)
≤ 0.01 / U(knots) (water)
db Increase in RMS Pressure Over Hydraulically Smooth Case
0
2
4
6
8
10
12
0.0001
0.001
0.01
0.1
1
RMS Roughness Height, h, in inches

Figure 2