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Fluxes of Tracers in

Wind and Water Tunnels

NOTICE

Final Report

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Colorado State University

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Abstract

The absorption process of particular matter at an air-water interface was studied by means of a Monte Carlo Simulation. This absorption process does not appear to be significantly different from similar processes over stationary boundaries. Especially an increased flux toward the boundary as the result of more effective particle removal due to wave action could not be observed. The particular nature of the tracer prevents this from happening.

FLUXES OF TRACERS IN WIND AND WATER TUNNELS

OBJECTIVES

The purpose of this investigation was to explore the absorption mechanism at an air-water interface. The assumption is that particulate matter through regular turbulent diffusion processes in the atmospheric boundary layer gets close to the interface. As the particles reach levels which are about one wave amplitude above the average interface a very intricate interaction between the waves and the path of the particle occurs.

One line of thought proposes that the waves will quickly and effectively clear the particles from that lowest layer of air and that as a result the concentration level would be very low. This would lead to a large concentration gradient resulting in a large flux toward the interface.

In order to investigate whether the wave would indeed more effectively remove the particles it was decided to simulate the details of the process in a Monte Carlo Simulation.

THE SIMULATIONThe particle

The particle is released from a fixed point. Its path is then traced time step by time step. At the beginning of the time step the particles average longitudinal velocity is determined according to its distance from the theoretical wall, using a logarithmic velocity distribution. Then the turbulent component of the particles longitudinal velocity is determined by obtaining a random number, normally distributed, with mean zero and a standard deviation appropriate for the wall distance of the particle. The combination of average

and turbulent longitudinal velocity determines how far the particle will move horizontally in the time step. In order to determine its vertical displacement again a random number, normally distributed and properly scaled will determine the vertical velocity fluctuation to be superimposed on the particles fall velocity. The combination of fall velocity and turbulent vertical velocity determines the vertical displacement in the time step. By repeating the procedure the particles path can be traced as a function of time until it either reaches a given downstream position or until it gets deposited at the interface.

The wave

Every time a particle is released the same point of an identical wave train is passed under the release point. In other words at a fixed travel time the wave surface will look the same for all particles. The fact that each particle is exposed to the same wave train corresponds to an experiment where a puff of tracer is released at a given time. The waves were considered two-dimensional, and accordingly the lateral motion of the particles was not traced.

The absorption

A particle was considered absorbed when its y-coordinate was below the instantaneous water level. By interpolation in time and space the actual point of absorption was determined.

The only exceptions to this procedure are those computer runs where either the windward or leeward side of the wave was considered to reflect particles perfectly. In case of reflection it was assumed that the surface acts like a mirror.

THE PARAMETERS

Velocity profile

The longitudinal velocity was assumed to follow the logarithmic distribution

$$\bar{u}(y) = u_* [2.5 \ln \frac{y}{k_s} + 8.5]$$

with $\bar{u}(\delta) = .98 u_\infty$; where $\bar{u}$ is the average longitudinal velocity at a distance y from the average wall position, u_* is the shear velocity, k_s is the effective roughness height, δ is the boundary layer thickness, and u_∞ the free stream velocity.

When a particle falls below about $y = 0$ in between two waves, two cases are investigated:

Type 1: for $y < y_{\min}$ $\bar{u}(y) = c$ where $y_{\min}$ is the location where $\bar{u}(y) = c$ in the logarithmic velocity distribution, and c is the wave celerity.

Type 2: for $y < y_{\min}$ $\bar{u}(y) = 0$ where $y_{\min}$ is the location where $\bar{u}(y_{\min}) = 0$.

It was the purpose of simulation runs 2 through 11 to investigate possible effects due to these different assumptions. Except for the different velocity profiles all other parameters were to be kept exactly the same, including the path of the particle and the wave train. This was accomplished by using the same feed numbers in the random number generator.

Reflection characteristics of water surface

The concept of reflection was motivated by the idea that due to differences in turbulent characteristics on the windward and leeward

side of a single wave (possible separations) this could be accounted for by changing the reflection probability. Conceptually the probability for reflection could be a continuous function of the slope of the water level. But only three extreme cases were tested; run 15 with no reflection whatsoever, run 16 with perfect reflection on the windward side and perfect absorption on the leeside, and run 17 the opposite of run 16.

Vertical velocity fluctuations

Considering the wave action the vertical velocity fluctuations appear very uncertain near the wall. The assumed standard deviations were those recommended by Hinze. But in run 19 we duplicated run 18 with reduced fluctuations for $y/\delta < 0.1$.

Wave characteristics

Amplitude and wavelength were varied relatively arbitrarily, that is with little attention to physical reality, but with the main purpose to detect some effect; runs 20 through 27.

Wave train

While in most of the experiments the wave train was a sine-wave traveling at 1 ft/sec in runs 32 through 35 these characteristics were varied. Runs with a stationary sine wave, with a flat (but fluid dynamically rough) wall, and with a time series (2nd order autoregressive process) were performed.

Fall velocity

Finally a series of three runs (31, 40, and 41) was conducted where the particle fall velocity was set to zero.

RESULTS

Computer program

In the Appendix a listing of the computer program (Fortran IV) is presented. The extensive use of comment-cards makes additional comments unnecessary.

Special care was used in the generation of the random (really pseudo-random) numbers. In order to avoid any possible, yet very undesirable correlations two totally independent generators were used.

Velocity profile

Figures 1 through 6 show the actual absorption points for the 100 particles released. Runs 2, 7, and 10 were identical but using different sets of random numbers, all with velocity profile type 1. Runs 3, 8, and 11 were identical but with different sets of random numbers, now with profile type 2. In order to show only the effect of the changed profile matching runs used the same random number, 2 and 3; 7 and 8; and lastly 10 and 11.

Comparing runs 2, 7, and 10 gives a feeling for the randomness of the process. Though the actual absorption points are slightly shifted, absorption happens almost always on the same wave. Note the significantly reduced chance of absorption on the leeward side of the waves. The number of particles absorbed between release point and 5 ft further downstream is in the range 87 to 93 percent. Matching runs show the same percentage points.

Conclusion: The longitudinal velocity profile in the layer covered by the wave has essentially no effect on the absorption process. This is because after a particle is "trapped" between two waves, it will almost certainly stay there until absorbed.

Reflection characteristics

Figure 7 shows results from run 15. This run serves as a reference with no reflection. It is almost a duplication of run 10, but the particles are traced further downstream such that all particles got absorbed.

Run 16, figure 8, shows the same situation but with perfect reflection on the leeward side of the waves. There is very little change when compared with run 15, since few particles get absorbed on the leeward side in the case of no reflection.

Run 17, figure 9, shows a significantly different pattern. The particles, when reflected on the windward side are kicked over the top of the wave. But almost invariably they will get absorbed right behind the first wave crest they passed over. In general then the travel distance is only increased by about $1/2$ wavelength. This is illustrated by the fact that in run 16, 87 percent of the particles were absorbed after 8 ft and in run 17 this had dropped only to 85 percent. Since identical particle paths were used in the two runs between release point and first impact point the difference in percentage absorbed, though small, must be considered statistically significant.

Conclusion: Because of the flow pattern it is considered very likely that the probability for absorption is not uniform. But the changes in absorption location are only in the order of magnitude of $1/2$, perhaps the very most $1 \frac{1}{2}$ wavelength. From an overall point of view this does not appear significant.

Vertical velocity fluctuations

Run 19 was a duplication of run 18 but the vertical velocity fluctuations were reduced by 50 to 75 percent for $y = 0$ to

$y = 0.1 \delta$. These runs were performed with 500 particles. After 5 ft, 448 were absorbed in either case.

Conclusion: The intensity of the vertical velocity fluctuations seems to have no significant effect on the overall absorption process.

Wave characteristics

Runs 20 through 27 showed the following wave characteristics:

Run #	Amplitude inches	Wave Length ft	Number of particles absorbed at 5 ft
20	.5	2.0	78
21	1.0	2.0	87
22	2.0	2.0	99
23	1.0	1.0	75
24	1.0	1.5	83
25	1.0	2.0	87 (same run as 21)
26	1.0	2.5	65
27	1.0	3.0	71

In the first three runs the effect of the amplitude was investigated. The higher the waves the earlier the particles got absorbed. This verifies the concept that after a particle has dropped between two waves it will not leave that area. In the case of larger amplitudes this trapping occurs earlier leading to a more effective absorption process.

Runs 23 through 27 were to illustrate possible effects due to the wavelength (with the same wave amplitude). There is no systematic pattern in the number of particles absorbed at $x = 5$ ft. The percentage ranges between 65 percent and 87 percent, a random variation much more significant than the systematic changes due to amplitude variation.

Conclusion: Wave height does systematically effect the absorption process. The higher the waves the earlier (the faster) the absorption.

Considering the randomness of the overall process (see runs 2, 7, and 10) as well as the random effect due to wavelength, this systematic change due to wave height does not appear very significant.

Wave train

In runs 32 through 35 the effect of wave train characteristics were investigated. Run 32 serves as a reference (moving sinusoidal wave). In Run 33, the wave celerity was set at zero, not to simulate any physically realistic situation but to investigate an extreme. Run 34 is based upon a flat boundary (but unchanged velocity distribution and velocity fluctuations). Finally run 35 is a time series with the same average characteristics as run 32.

The variation in the number of particles absorbed is well within the limits of the natural randomness of the process, with the exception of run 34. As anticipated from the effect of amplitude, this run shows the lowest absorption rate. The following table summarizes the results.

Run #	Amplitude	Wave Celerity	Number Absorbed at 5 ft	Average Distance Traveled L (ft)	σ_L	Height When Absorbed H (in)	σ_H
32	.5	1.0	706	4.24	.53	+.21	.27
33	.5	.0	686	4.22	.54	+.24	.24
34	.0	.0	610	4.28	.48	+.0	.0
35	.5	1.0	683	4.15	.50	+.35	.36

Figures 10, 11 and 12 show the location of impact for runs 32, 33, and 35. Note in run 35 the different pattern due to the time series. The varying wave heights are clearly visible.

Figure 13 through 16 show the vertical distribution of particles at the downstream end of the test section ($x = 5$ ft). Run 34 shows higher concentrations close to the wall than the others, again illustrating the effect of amplitude on the efficiency of the absorption process. Other differences among the figures appear to be insignificant.

Conclusion: Looking at the randomness of the process (σ_L and σ_H) variations in averaged characteristics appear clearly insignificant. The shape of the wave train and its celerity does not much effect the absorption process.

Fall Velocity

Finally in a last series of 3 runs, a situation was simulated with a tracer of zero fall velocity. Run 39 was attempting to simulate a realistic situation, as it could occur in a wind tunnel. The free stream velocity was 20 ft/sec, $\delta = 5.0$ inches, the wave amplitude .07 inches, the wave length .11 ft with a celerity of 1.5 fps. After 7.75 ft 2.4% of the particles were absorbed (based upon a sample of 1,000 particles). The vertical distribution at $x = 7.75$ ft is given in Figure 17.

In run 40 again the effect of wave speed was investigated. Arbitrarily, it was set at zero. Absorption was now 2.3%. Figure 18 shows the concentration distribution essentially unchanged.

In run 41 the amplitude was set to 0, again not resulting in any significant change.

CONCLUSIONS

The results of this investigation indicate that the efficiency with respect to absorption of particulate matter at an air-water interface with waves is not significantly different from the one at a stationery interface with similar roughness characteristics.

The concept of low concentration levels close to the boundary (as a result of wave action) and correspondingly high concentration gradient and high flux toward the boundary does not really apply, because of the noncontinuous character of the tracer.

fig. 1

POSITIONS OF PARTICLES HITTING BOUNDARY

RAIN

Fig. 2 POSITIONS OF PARTICLES HITTING BOUNDARY

RAIJN

ANGLE)

POSITIONS OF PARTICLES HITTING BOUNDARY

RAUN

ANGLE)

Run 8

16

POSITIONS OF PARTICLES HITTING BOUNDARY

RAUN

ANGLE

POSITIONS OF PARTICLES HITTING BOUNDARY

RAIN

ANGLE

19

20

Fig. 8

POSITIONS OF PARTICLES HITTING BOUNDARY

RAUN

Fig. 9

POSITIONS OF PARTICLES HITTING BOUNDARY

RAUN

Fig. 10

POSITIONS OF PARTICLES HITTING BOUNDARY

RAUNPI

Fig. 12

POSITIONS OF PARTICLES HITTING BOUNDARY

RAUNPI

Fig. 13 NUMBER OF PARTICLES IN EACH VERTICAL INTERVAL AT DOWNSTREAM BOUNDARY

Fig. 14 NUMBER OF PARTICLES IN EACH VERTICAL INTERVAL AT DOWNSTREAM BOUNDARY

Fig. 15 NUMBER OF PARTICLES IN EACH VERTICAL INTERVAL AT DOWNSTREAM BOUNDARY

28

Fig. 16 NUMBER OF PARTICLES IN EACH VERTICAL INTERVAL AT DOWNSTREAM BOUNDARY

Fig. 18

NUMBER OF PARTICLES IN EACH VERTICAL INTERVAL AT DOWNSTREAM BOUNDARY

Fig. 19

NUMBER OF PARTICLES IN EACH VERTICAL INTERVAL AT DOWNSTREAM BOUNDARY

APPENDIX**Listing of
Simulation Program**

PROGRAM TRACE

```

1 (INPUT,OUTPUT,TAPES=INPUT,TAPE6=OUTPUT)
  DIMENSION UP1(11),UP2(11),RUI(1000),XNP(100),XAV(100),YNP(20),
  YV(20),XRN(19),YTS(51),AW(1000),YW(1000)
5   COMMON QU,FN,XRN,E,PI,RP
      E=2.71828182845
      PI=3.14159265
      DO 101 I=1,100
101  XAV(I)=0.1*FLOAT(I)-0.05
10   C**** READ IN DATA FOR NORMAL RANDOM NUMBER GENERATOR
      READ(5,500)(XRN(I),I=1,19)
      C**** READ IN RELATIVE TURBULENT INTENSITIES
      READ(5,502)(UP1(N),N=1,11)
      READ(5,502)(UP2(N),N=1,11)
15   C**** READ IN FREE STREAM VELOCITY, BOUNDARY LAYER THICKNESS,
      C**** AND BED ROUGHNESS SIZE
      READ(5,505)UMEAN,DEL,XKS
      C**** READ IN NUMBER OF PARTICLES AND TIME INTERVAL
      READ(5,503)NP,T
20   C**** GENERATE INITIAL RANDOM NUMBER FOR EACH PARTICLE
      RU=0.0
      RP=0.0
      DO 102 J=1,NP
      CALL RAUNPI
      RUI(J)=RP
25   102 CONTINUE
      C**** READ IN LIMITS FOR HORIZONTAL DISTANCE AND NUMBER OF
      C**** STEPS, INITIAL PARTICLE HEIGHT, AND FALL VELOCITY
      1 READ(5,504)XDIST,NS,YC,VF
      30 IF (EOF(5))3,2
      C**** READ IN AMPLITUDE, WAVE SPEED (CELERITY), AND WAVELENGTH
      2 READ(5,505)A,C,XL
      C**** READ IN VELOCITY PROFILE TYPE
      READ(5,506)IVPT
35   C**** READ IN PROBABILITIES OF REFLECTION
      READ(5,507)PU,PD
      IR=INT(2.-PU-PD)
      C**** DETERMINE SHEAR VELOCITY (ASSUME VXAVG=0.98*UMEAN AT
      C**** Y=DEL), AND HEIGHT AT WHICH VXAVG=0 AND VXAVG=C
      USTAR=0.98*UMEAN/(2.50*ALOG(DEL/XKS)+8.50)
      YWALL=XKS/E**((8.50/2.50)
      YVMIN=XKS/E**((0.4*C/USTAR)-3.40)
      C**** PRINT OUT INPUT DATA
      WRITE(6,601)UMEAN,DEL,XKS
45   WRITE(6,602)
      WRITE(6,603)(UP1(N),N=1,11)
      WRITE(6,604)(UP2(N),N=1,11)
      WRITE(6,605)USTAR,YWALL,YVMIN
      WRITE(6,606)NP,T
50   WRITE(6,607)XDIST,NS,YC,VF
      WRITE(6,610)A,C,XL
      WRITE(6,611)IVPT
      WRITE(6,613)PU,PD
      C**** INITIALIZE SUMS AND COUNTERS
55   LV=0
      LW=0
      XWSUM=0.0
      YWSUM=0.0
      XWSQ=0.00

```

PROGRAM	TRACE	CDC 6400 FTN V3.0-p365 OPT=1 10/25/74 00.01.53. PAGE 2
60	YWSQ=0.00 DO 103 M=1,20 YV(K)=0.05*(A+DEL)*(0.5+FLOAT(K-1))-A YNP(K)=0.0	
65	103 CONTINUE DO 104 I=1,100 XNP(I)=0.0	
70	104 CONTINUE F=2.0*PI/XL C**** EACH EXECUTION OF DO LOOP 2000 MOVES ONE PARTICLE DO 2000 NN=1,NP X=0.0 Y=Y0 TE=T RU=RUI(NN) RP=RUI(NN)	
75	C**** EACH EXECUTION OF DO LOOP 1000 MOVES PARTICLE ONE STEP DO 1000 M=1,NS C**** COMPUTE POSITION AS FRACTION OF DEL TO DETERMINE WHICH C**** RELATIVE TURBULENT INTENSITIES SHOULD BE USED	
80	YY=Y/DEL FY=(10.*YY)-AINT(10.*YY) IYY=INT(YY*2.0) GO TO (301,302,302) IYY	
85	301 K=1 L=1 GO TO 303 302 K=INT(10.*YY)+1 L=K+1	
90	C**** COMPUTE HORIZONTAL VELOCITY 303 GO TO (304,306) IYPT 304 IYM=INT((Y+DEL)/(YVMIN+DEL)+1.0) GO TO (305,308,308) IYM 305 VXAVG = C GO TO 309	
95	306 IYM=INT((Y+DEL)/(YWALL+DEL)+1.0) GO TO (307,308,308) IYM 307 VXAVG = 0.0 GO TO 309	
100	308 VXAVG=USTAR*(2.50*ALOG(Y/XKS)+8.50) 309 U1=((UP1(L)-UP1(K))*FY+UP1(K))*UMEAN CALL RANO UL1=U1*RN VX=VXAVG+UL1	
105	C**** COMPUTE VERTICLE VELOCITY U2=((UP2(L)-UP2(K))*FY+UP2(K))*UMEAN CALL RANO VY=U2*RN-VF C**** MOVE PARTICLE THROUGH ONE TIME INTERVAL (ONE STEP) X=X+VX*T Y=Y+(VY*T*12.)	
110	C**** CHECK--PARTICLE HEIGHT VS. BOUNDARY LAYER THICKNESS IY=INT(Y/DEL*2.) GO TO (400,400,2000,2000) IY	
115	C**** CHECK--PARTICLE HEIGHT VS. WAVE AMPLITUDE 400 IY=INT((Y+DEL)/(A+DEL)+1.) GO TO (401,407) IY C**** COMPUTE WATER SURFACE HEIGHT AT GIVEN X AND T 401 ANGLE=F*(X-C*TE)	

```
120      YWALLT=A*SIN(ANGLE)
      C**** CHECK--PARTICLE HEIGHT VS. WATER SURFACE HEIGHT
      IYW=INT((Y+DEL)/(YWALLT+DEL)+1.)
      GO TO (402,407,407) IYW
      C**** REFLECT PARTICLE IF APPROPRIATE
125      402 GO TO (403,403,410) IR
      403 CALL RAINPT
      DY=2.0+COS(ANGLE)
      IDY=INT(DY)
      GO TO (404,405,405) IDY
130      404 INP=INT((PU+1.)/(RP+1.))+1.)
      GO TO (410,406) INP
      405 INP=INT((PD+1.)/(RP+1.))+1.)
      GO TO (410,406) INP
      406 YDELTA=YWALLT-Y
      Y=YWALLT+YDELTA
135      C**** CHECK--HORIZONTAL POSITION VS. LIMIT
      407 IX=INT(X/XDIST+1.)
      GO TO (408,409) IX
      408 XP=X
      YP=Y
140      1000 TE=TE+T
      C**** INTERPOLATE FOR POSITION OF PARTICLES STILL IN MOTION AT
      C**** DOWNSTREAM BOUNDARY. RECORD RESULTS
      409 LV=LV+1
      YF=YP+((Y-YP)*((XDIST-XP)/(X-XP)))
145      IV=1+INT((YF+A)/(DEL+A)*20.)
      YNP(IV)=YNP(IV)+1.
      GO TO 2000
      C**** INTERPOLATE FOR POSITION OF ABSORBED PARTICLES
150      410 LW=LW+1
      TI=T/10.0
      TEI=TI
      TE=TE-T+TI
      DO 800 LL=1,10
155      X=XP+VX*TEI
      Y=YP+(VY*TEI*12.0)
      ANGLE=F+(X-C*TE)
      YWT=A*SIN(ANGLE)
      IYWT=INT((Y+DEL)/(YWT+DEL)+1.)
      GO TO (401,799) IYWT
160      799 TEI=TEI+TI
      TE=TE+TI
      800 CONTINUE
      C**** RECORD INFORMATION ON ABSORBED PARTICLES
165      801 IXAV=INT(10.*X)+1
      XNP(IXAV)=XNP(IXAV)+1.
      AW(LW)=ANGLE
      YW(LW)=YWT
      XWSUM=XWSUM+X
      XWSQ=XWSQ+X*X
      YWSUM=YWSUM+YWT
      YWSQ=YWSQ+YWT*YWT
170      2000 CONTINUE
      C**** COMPUTE STATISTICS FOR ABSORBED PARTICLES
175      FLW=FLOAT(LW)
      XWAVG=XWSUM/FLW
      XWSTD=SQRT((FLW*XWSQ-XWSUM*XWSUM)/(FLW*(FLW-1.)))
      YWAVG=YWSUM/FLW
```

```
YVSTD=SQRT((FLW*YWSO-YWSUM*YWSUM)/(FLW*(FLW-1)))
```

```
C****
C****
```

```
COMPUTE LIMITS FOR WRITING SOME RESULTS (ELIMINATE LOWER
AND UPPER INTERVALS WHICH CONTAIN NO PARTICLES)
```

180

```
DO 105 I=1,100
XINP=XNP(I)
IZI=INT((100.-XINP)/100.)*1
GO TO (106,105) IZI
```

185

```
105
106
```

```
CONTINUE
LLPR=I-2
DO 107 I=1,100
YINP=XNP(101-I)
IZJ=INT((100.-YINP)/100.)*1
GO TO (108,107) IZJ
```

190

```
107
108
```

```
CONTINUE
LUPR=103-I
```

```
C****
```

```
PRINT OUT DESIRED INFORMATION
```

195

```
WRITE(6,615) LW, LV
WRITE(6,614) (XAV(I), XNP(I), I=LLPR, LUPR)
WRITE(6,612) (YV(I), YNP(I), I=1, 20)
WRITE(6,616) XWAVG, XWSTD, YWAVG, YWSTD
CALL MAPA(5, YNP, YV, 1, 20, HL, HH, VL, VH, 10HQUANTITY, 10HWEIGHT, .80
1HNUMBER OF PARTICLES IN EACH VERTICAL INTERVAL AT DOWNSTREAM BOUND
2ARY, .1)
CALL MAPA(5, AW, YW, 1, LW, HL, HH, VL, VH, 10HANGLE(RAD), 10HSIN(ANGLE),
13HPOSITIONS OF PARTICLES HITTING BOUNDARY, 1)
GO TO 1
```

200

```
C****
```

```
READ FORMAT STATEMENTS
```

205

```
500 FORMAT(10F8.3)
501 FORMAT(3F10.0)
502 FORMAT(11F7.5)
503 FORMAT(110,F10.0)
504 FORMAT(F10.0,110,2F10.0)
505 FORMAT(3F10.0)
506 FORMAT(15)
507 FORMAT(2F5.0)
508 FORMAT(2F10.0)
```

210

```
C****
```

```
WRITE FORMAT STATEMENTS
```

215

```
601 FORMAT(1H1,31HAVERAGE LONGITUDINAL VELOCITY =,F6.2,4H FPS/1H ,
129HTHICKNESS OF BOUNDARY LAYER =,F10.6,4H IN./1H ,15HRED ROUGHNESS
2 =,F10.6,4H IN.)
602 FORMAT(1H0/1H ,5HY/DEL,8X,3H0.0,8X,3H0.1,8X,3H0.2,8X,3H0.3,8X,
13H0.4,8X,3H0.5,8X,3H0.6,8X,3H0.7,8X,3H0.8,8X,3H0.9,8X,3H1.0)
603 FORMAT(1H0,9HUP1/UMEAN,10(2X,F7.5,2X),2X,F7.5)
604 FORMAT(1H0,9HUP2/UMEAN,10(2X,F7.5,2X),2X,F7.5)
605 FORMAT(1H0/1H ,16HSHEAR VELOCITY =,F10.6,4H FPS/
11H ,24HADJUSTED WALL POSITION =,F8.5,4H IN./1H ,
2274Y AT WHICH VAVG EQUALS C =,F8.5,4H IN.)
```

220

225

```
606 FORMAT(1H0/1H ,35HNUMBER OF PARTICLES TO BE TRACED = ,15/
11H ,16HTIME INTERVAL = ,F5.3,4H SEC)
607 FORMAT(1H ,39HLONGITUDINAL DISTANCE TO BE TRAVELLED =,F8.2,3H FT/
11H ,37HMAXIMUM NUMBER OF STEPS TO BE TAKEN =,15/1H ,10HINITIAL VE,
217HRTICAL POSITION =,F8.2,4H IN./1H ,24HPARTICLE FALL VELOCITY =,
3F7.4,7H FT/SEC)
```

230

```
608 FORMAT(1H-///1H-,18HVERTICAL POSITION ,F5.2,16H FEET DOWNSTREAM//
11H ,26HPARTICLE HEIGHT (IN.),6X,19HTIME ELAPSED (SEC.),
26X,10HINITIAL RU,6X,5HORDER//
3(1H ,15,11X,F7.4),15X,F6.3,14X,F8.6,8X,13))
```

235

```
609 FORMAT(1H-///1H-,34HPOSITION OF PARTICLES HITTING WALL//1H ,
18HPARTICLE,6X,25HDOWNSTREAM DISTANCE (FT.),6X,
```

247

212HHEIGHT (IN.),6X,19HTIME ELAPSED (SEC.),6X,12HANGLE (RAD.),6X,
 310HINITIAL RU,6X,5HOFDER//
 411H .15,18Y,F7.4,17X,F7.4,16X,F5.3,16X,F7.4,10X,F8.6,7X,I3))
 610 FORMAT(1H0/1H,11HAMPLITUDE =.F8.3,4H IN./1H,12HWAVE SPEED =,
 1F8.3,4H FPS/1H,12HWAVELENGTH =.F8.3,4H FT.)
 611 FORMAT(1H0/1H,24HVELOCITY PROFILE IS TYPE,15,5X,
 142HTYPE 1...VXAVG = C IF Y IS LESS THAN YVMIN/
 21H,34X,42HTYPE 2...VXAVG = 0 IF Y IS LESS THAN YWALL)

245

612 FORMAT(1H0/1H,61HNUMBER OF PARTICLES IN VERTICAL GROUPS AT DOWNST
 1REAM BOUNDARY//1H,12HHEIGHT (IN.),10X,16HNO. OF PARTICLES/
 211H,3X,F6.3,21X,F5.0))

250

613 FORMAT(1H0/1H,63HPCBABILITY PARTICLE IS REFLECTED AFTER HITTING
 1UPSTREAM FACE =.F5.3/1H,65HPPROBABILITY PARTICLE IS REFLECTED AFTE
 2R HITTING DOWNSTREAM FACE =.F5.3)

255

614 FORMAT(///1H,19HMEAN DISTANCE (FT.),5X,16HNO. OF PARTICLES/
 111H,3X,F5.2,22X,F5.0))
 615 FORMAT(//1H,30HNUMBER OF PARTICLES ABSORBED =.15/1H,57HNUMBER OF
 1 PARTICLES STILL IN AIR AT DOWNSTREAM BOUNDARY =.15)
 616 FORMAT(//1H,42HSTATISTICS FOR PARTICLES HITTING BOUNDARY /5X,41HA
 1VERAGE LONGITUDINAL DISTANCE TRAVELLED =.F7.3,4H FT./10X,20HSTANDA
 2RD DEVIATION =.F7.3/5X,41HAVERAGE VERTICAL POSITION WHEN ABSORBED
 3=.F7.3,4H IN./10X,20HSTANDARD DEVIATION =.F7.3)

267

3 STOP
 END

SYMBOLIC REFERENCE MAP

ENTRY POINTS

4052 TRACE

VARIABLES	SN	TYPE	RELOCATION
5625 A	REAL		5670 ANGLE REAL
10373 AW	REAL	ARRAY	5626 C REAL
5614 DEL	REAL		5673 DY REAL
25 E	REAL	//	5646 F REAL
5712 FLW	REAL		5655 FY REAL
5727 HH	REAL		5726 HL REAL
5611 I	INTEGER		5674 IDY INTEGER
5717 II	INTEGER		5675 INP INTEGER
5633 IR	INTEGER		5703 IV INTEGER
5630 IVPT	INTEGER		5677 IX INTEGER
5711 IXAV	INTEGER		5667 IY INTEGER
5660 IYM	INTEGER		5672 IYW INTEGER
5710 IYWT	INTEGER		5656 IYY INTEGER
5721 IZI	INTEGER		5724 IZJ INTEGER
5620 J	INTEGER		5645 K INTEGER
5657 L	INTEGER		5706 LL INTEGER
5722 LLPR	INTEGER		5725 LUPR INTEGER
5637 LV	INTEGER		5640 LW INTEGER
5653 M	INTEGER		5612 N INTEGER
5647 NN	INTEGER		5616 NP INTEGER
5622 NS	INTEGER		5632 PD REAL
26 PI	REAL	//	5631 PU REAL
1 RN	REAL	//	27 RP REAL
0 RU	REAL	//	5760 RUI REAL
5617 T	REAL		5652 TE REAL
5705 TEI	REAL		5704 TI REAL
5663 UL1	REAL		5613 UMEAN REAL
5732 UP1	REAL	ARRAY	5745 UP2 REAL

37

SUBROUTINE RAUNPI

C**** SUBROUTINE RAUNPI GENERATES UNIFORMLY DISTRIBUTED RANDOM
 C**** NUMBERS. NEW NUMBER IS PRODUCED BY ADDING *PI* ON TO
 C**** PREVIOUS NUMBER, RAISING TO EIGHTH POWER, AND USING
 C**** ONLY THE DECIMAL PORTION. THIS SUBROUTINE IS USED TO
 C**** GENERATE THE INITIAL RANDOM NUMBER FOR EACH PARTICLE,
 C**** AND TO GENERATE THE RANDOM NUMBER WHICH IS USED TO
 C**** DETERMINE WHETHER A PARTICLE SHOULD BE REFLECTED.

DIMENSION XRN(19)

COMMON RU,PN,XRN,E,PI,RP

Z = PI + RP

Z2=Z*Z

Z4= Z2*Z2

Z8 = Z4*Z4

RP= Z8 - AINT(Z8)

RETURN

END

SYMBOLIC REFERENCE MAP

ENTRY POINTS

1 RAUNPI

VARIABLES	SN	TYPE	RELOCATION				
25 E		REAL	//	26 PI	REAL	//	
1 PN		REAL	//	27 RP	REAL	//	
0 RU		REAL	//	2 XRN	REAL	ARRAY	//
11 Z		REAL		12 Z2	REAL		
13 Z4		REAL		14 Z3	REAL		

38

INLINE FUNCTIONS TYPE ARGS
 AINT REAL 1 INTRIN

COMMON BLOCKS LENGTH
 // 24

STATISTICS
 PROGRAM LENGTH 158 13
 BLANK COMMON 308 24

SUBROUTINE RAUN

C**** SUBROUTINE RAUN GENERATES UNIFORMLY DISTRIBUTED RANDOM
 C**** NUMBERS. NEW NUMBER IS PRODUCED BY ADDING #E# ON TO
 C**** PREVIOUS NUMBER, RAISING TO EIGHTH POWER, AND USING
 C**** ONLY THE DECIMAL PORTION. THIS SUBROUTINE IS USED TO
 C**** GENERATE THE RANDOM NUMBERS WHICH ARE REQUIRED BY THE
 C**** SUBROUTINE WHICH GENERATES NORMALLY DISTRIBUTED RANDOM
 C**** NUMBERS (SUBROUTINE RANO).

DIMENSION XRN(19)
 COMMON RU,PN,XRN,E,PI,RP
 Z = E *RU
 Z2=Z*Z
 Z4= Z2*Z2
 Z8 = Z4*Z4
 PU= Z8 - AINT(Z8)
 PFTURN
 END

SYMBOLIC REFERENCE MAP

ENTRY POINTS

1 RAUN

VARIABLES	SN	TYPE	PELOCATION
25 E		REAL	//
1 RN		REAL	//
0 PU		REAL	//
11 Z		REAL	
13 Z4		REAL	

26 PI	REAL	//
27 RP	REAL	//
2 XRN	REAL	ARRAY //
12 Z2	REAL	
14 Z8	REAL	

39

INLINE FUNCTIONS TYPE ARGS

AINT REAL 1 INTRIN

COMMON BLOCKS LENGTH

// 24

STATISTICS

PROGRAM LENGTH	158	13
BLANK COMMON	308	24

SUBROUTINE RANO

C**** SUBROUTINE RANO GENERATES NORMALLY DISTRIBUTED RANDOM
 C**** NUMBERS. EACH NUMBER IS PRODUCED BY USING A UNIFORMLY
 C**** DISTRIBUTED RANDOM NUMBER AS A CUMULATIVE PROBABILITY
 C**** DENSITY. THE RANDOM NUMBER IS THEN COMPUTED BY
 C**** INTERPOLATING BETWEEN NORMALLY DISTRIBUTED NUMBERS
 C**** SUPPLIED AS INPUT (XRN). THESE RANDOM NUMBERS ARE USED
 C**** IN COMPUTING THE INSTANTANEOUS VELOCITIES.

DIMENSION XRN(19)
 COMMON PU,PN,XRN,E,PI,RP
 CALL RAUN
 CC = AINT(RU+.5)
 PR = RU*(2.*CC-1.)-CC+.1.
 IC95 = INT(PR/.95)
 IC99 = INT(PR/.99)
 IC = IC95*(IC99+1)+1
 GO TO (11,12,13), IC

11 CO = RR/.05
 I = INT(CO) - 9
 GO TO 14
 12 CO = RR/.01
 I = INT(CO) - 85
 GO TO 14
 25 13 CO = RR/.002
 I = INT(CO) - 481
 14 PN = (2.*CC-1.)*(XRN(I) + (CO-AINT(CO))*(XRN(I+1)-XRN(I)))
 RETURN
 END

SYMBOLIC REFERENCE MAP

ENTRY POINTS

1 RANO

VARIABLES	SN	TYPE	RELOCATION	75	CO	REAL
70 CC		REAL		76	I	INTEGER
25 E		REAL	/ /	72	IC95	INTEGER
74 IC		INTEGER		26	PI	REAL
73 IC99		INTEGER		27	RP	REAL
1 RN		REAL	/ /	0	RU	REAL
71 RR		REAL	/ /			
2 XRN		REAL	ARRAY / /			

EXTERNALS TYPE ARGS
 RAUN 0

INLINE FUNCTIONS TYPE ARGS
 AINT REAL 1 INTRIN INT INTEGER 1 INTRIN

STATEMENT LABELS

30 11 35 12 42 13
 46 14

COMMON BLOCKS LENGTH

/ / 24

CE22(

```
PROGRAM TIMSEP
1 (INPUT,OUTPUT,PUNCH,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7=PUNCH)
DIMENSION XRN(19),T(201),X(201)
COMMON RU,RN,XRN,E,PI,RP
E=2.71828182845
WRITE(6,601)
100 READ(5,501) (XRN(I),I=1,19)
READ(5,502) ALPHA1,ALPHA2,L
IF (EOF(5)) 103,101
101 RU=0.0
T(1)=0.0
CALL RANO
T(2)=RN
TSUM=RN
ATSUM=ABS(RN)
TSQ=RN*RN
NSC=0
M=L+1
DO 200 N=3,M
CALL RANO
T(N)=ALPHA1*T(N-1)+ALPHA2*T(N-2)+RN
TSUM=TSUM+T(N)
TSQ=TSQ+T(N)*T(N)
ATSUM=ATSUM+ABS(T(N))
IN=INT(T(N)*T(N-1)/ABS(T(N)*T(N-1))+2.)
GO TO (102,102,200) IN
102 NSC=NSC+1
200 CONTINUE
FL=FLOAT(L)
TAV=TSUM/FL
ATAV=ATSUM/FL
TSTD=SQRT((FL*TSQ-TSUM*TSUM)/(FL*(FL-1.)))
WRITE(6,602) ALPHA1,ALPHA2
WRITE(6,603) TAV,TSTD,ATAV,L,NSC
TASUM=0.0
TSUM=0.0
DO 300 I=2,M
T(I)=T(I)-TAV
TSUM=TSUM+T(I)
TASUM=TASUM+ABS(T(I))
300 X(I)=FLOAT(I)
X(1)=1.0
TAV=TSUM/FL
ATAV=TASUM/FL
TSUM=0.0
TASUM=0.0
DO 400 I=2,M
T(I)=T(I)/ATAV
TSUM=TSUM+T(I)
400 TASUM=TASUM+ABS(T(I))
TAV=TSUM/FL
ATAV=TASUM/FL
WRITE(6,604) TAV,ATAV
WRITE(6,605) (T(I),I=51,100)
CALL MAPA(5,X,T,M,HL,HH,VL,VH,10H DISTANCE,10H AMPLITUDE,26HREA
ILIZATION OF TIME SERIES,1)
WRITE(7,701) (T(I),I=51,100)
```

1234567890123456789012345678901234567890123456789012345678901234567890

```
51  FORMAT(10F8.3)
502 FORMAT(2F10.0,15)
601 FORMAT(1H1)
602 FORMAT(///1H-,*COEFFICIENTS FOR TIME SERIES ARE AS FOLLOWS*/
116X,*ALPHA1 =*,F6.2/16X,*ALPHA2 =*,F6.2)
603 FORMAT(///1X,15HAVERAGE VALUE =,F9.5//1X,20HSTANDARD DEVIATION =,
1F7.3//1X,19HAVERAGE AMPLITUDE =,F9.5//1X,28HNUMBER OF POINTS GENER
2ATED =,15//1X,34HNUMBER OF TIMES THE SIGN CHANGED =,15)
604 FORMAT(///1X,18HADJUSTED AVERAGE =,F9.5//1X,28HADJUSTED AVERAGE AM
1PLITUDE =,F9.5)
605 FORMAT(///1H,26HREALIZATION OF TIME SERIES/51/10(5X,F8.5)))
701 FORMAT((10F8.5))
GO TO 100
103 STOP
END
```

NUMBER OF CARDS = 73