Flutter Analysis for Identifying Tape Recorders

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Mechanical imperfections in every recorder cause speed variations (flutter) which have a frequency spectrum that is characteristic of both the *model* of recorder and of the *individual* recorder. The speed variations of the recorder cause fm sidebands around any signal recorded on that recorder. When the signal to be recorded contains a periodic signal, for instance power line hum, the sidebands on the recording can be measured, and converted into a flutter spectrum. By comparing the flutter spectrum found on the recording to that measured on the recorders, one may be able to identify the recorder which produced the recording. The theory is developed and a practical example is given.

Authors' Note:

In 1973 November, Chief Judge John J. Sirica of the U.S. District Court for the District of Columbia appointed an advisory panel to undertake an examination of the authenticity and integrity of tape recordings made in the offices of the President of the United States of America.

The counsel for the President and the Special Prosecutor as counsel for the Grand Jury agreed upon the selection and nomination of six technical experts to examine various tape recordings and to report their findings to the Court. The Court accepted the nominations of counsel for the respective parties, and on 1973 November 21, appointed Richard H. Bolt, Franklin Cooper, James L. Flanagan, John G. (Jay) McKnight, Thomas G. Stockham, Jr., and Mark R. Weiss as an advisory panel of expert witnesses to assist the Court.

On 1974 May 31, the panel submitted to the Court its final report, "The EOB Tape of June 20, 1972: Report on a Technical Investigation Conducted for the U.S. District Court for the District of Columbia by the Advisory Panel on White House Tapes." This report was available to the public from the Court at that time, but the supply is now exhausted.

Included in this report are thirteen technical notes which detail the scientific techniques used and the test results obtained. Although all six members of the panel wrote the body of the report and reviewed the technical notes, various groups of panel members wrote the technical notes themselves.

Technical Note 6, "Flutter Analysis for Identifying Tape Recorders," is reprinted verbatim below by the kind permission of the Court and the Special Prosecutor's Office.

The principal sources of information available to the panel were the tape recording labeled "EOB office–start 6/12/72, end 6/20/72," which is referred to as the evidence tape; the tape recorders that were thought to have been used in making the original recording and, later, rerecording a buzz tone on one section of the tape; and additional information about how the original recordings were made.

The principal items of equipment that were provided by the Court and used in the tests were seven Sony 800B recorders (one inoperative) from the Oval Office and Executive Office Building recording installations, a Uher 5000 recorder marked "Secret Service" and another Uher 5000 recorder with associated foot pedal, marked "Government Exhibits 60 and 60 B."

PRINCIPLES

When a magnetic tape is moving at a constant speed, a recorded signal having constant wavelength is reproduced as a constant frequency. In reality the tape drive mechanisms of all tape recorders have mechanical imperfections that cause the tape speed to vary slightly above and below its average value. The constant-wavelength recording is reproduced as a slightly varying frequency because the reproduced frequency is directly proportional to the reproducing speed. In other words, the signal is frequency modulated by the speed variations [1]. This effect is well known in the field of sound recording, and explained in detail in the references to this technical note. Because the frequency variations are directly proportional to the speed variations, and because the audible effect is closely related to the frequency variations, all three processes have come to be known colloquially as "flutter" [2]. The context usually makes the specific meaning clear.

The peak amplitude of flutter is defined as $F = \Delta f/f_0$, where f_0 is the average frequency of the signal and Δf is the frequency deviation (that is, the difference between the maximum or minimum instantaneous frequency of the signal and its average frequency) produced by the speed variations. The frequencies at which the speed variations occur are called flutter-modulating frequencies f_m. A plot or table of the flutter amplitudes as a function of the flutter-modulating frequency is called a flutter spectrum.

The flutter-modulating frequencies are determined by the rotational frequencies of such mechanical elements as the capstan and its driving system, the reels and their driving system, etc. The flutter amplitudes are determined by the magnitudes of the mechanical imperfections of these same elements [3]. Thus it is usually possible to use the flutter spectrum found on a recorded tape to identify both the model of the tape recorder used to make the recording and, with less certainty, the individual recorder itself.

Analysis of the flutter-modulating frequencies and amplitudes is usually done directly by frequency demodulation of the modulated signal and a spectrum analysis of this demodulated flutter signal [4]. Commercially available flutter meters and analyzers are intended for use with a standard test frequency of 3150 Hz; they employ a frequency demodulator which operates over a restricted frequency range. They directly measure the frequency f_m and amplitude F of the flutter.

In using flutter analysis to identify the tape recorder used to record a particular tape, one is very unlikely to have the standard 3150-Hz test tone. It is not uncommon, however, when the recorder is operated from ac power lines, for a low-level "hum" to be recorded on the tape due to leakage of hum into the recording system. Since the power companies regulate this frequency rather carefully, the 60-Hz hum can be used as the "test tone" for flutter analysis. Since commercial flutter meters do not function with hum frequencies (e.g., 60 Hz), a special demodulator would need to be constructed.

An alternate technique of flutter analysis having great flexibility is the use of direct spectrum analysis of the hum signal and its sidebands. We call this "flutter sideband spectrum analysis." From traditional frequency-modulation theory [5],

$$e = A \{ J_0(m_f) \sin 2\pi f_0 t + J_1(m_f)[\sin 2\pi(f_0 + f_m)t - \sin 2\pi(f_0 - f_m)t] + \cdots \}$$

where e is the instantaneous value of the waveform (hum signal plus sidebands),
A is an arbitrary constant determining the amplitude of all components,
$J_n(m_f)$ are Bessel functions of the nth order,
m_f is the modulation index, $\Delta f/f_m$
Δf is the frequency deviation
f_m is the modulating frequency and
f_0 is the frequency of the signal, which is called a "carrier" in frequency-modulation theory.

The first term in the equation represents the carrier with frequency f_0 and relative amplitude $J_0(m_f)$. The second term represents two sidebands with frequencies $f_{s1} = (f_0 - f_m)$ and $f_{s2} = (f_0 + f_m)$, and relative amplitudes $J_1(m_f)$.

For small values of the modulation index m_f, say $m_f < 0.5$, $J_0(m_f) \geq 0.94 \approx 1$, $J_1(m_f) = m_f/2$, and higher order terms are negligible.

From this we see that the ratio of sideband amplitude a_s to carrier amplitude a_0 for small modulation indices is $a_s/a_0 = m_f/2$. But we want flutter $F = \Delta f/f_0$, not modulation index m_f:

$$F = \Delta f/f_0 = (\Delta f/f_m)\,(f_m/f_0) = m_f(f_m/f_0)$$

and finally

$$F = 2(a_s/a_0)\,(f_m/f_0).$$

The preceding approximation is valid, for instance, when a 60-Hz carrier frequency is used to measure flutter whose modulating frequency is greater than 0.5 Hz, and whose amplitude is less than 4 per mill.[1]

As we have shown, the flutter spectrum and the flutter sideband spectrum are not the same, but they do contain the same information, and either can be calculated directly from the other by using the formula given before. In order to compare the flutter on one recording to the flutter on another recording, we may compare the flutter sideband spectra directly. However, when we wish to compare the flutter on a recording to the mechanical elements of the tape recorder that cause the flutter, it is necessary to convert the flutter sideband spectra to flutter spectra.

MEASUREMENT OF FLUTTER SIDEBAND SPECTRA AND CALCULATION OF FLUTTER SPECTRA ON THE EVIDENCE TAPE

On an ideal tape recording, hum signals would be so small as to be virtually undetectable. However, examination of the speech recording section of the evidence tape revealed that the recording contained a large power-line hum component that had been picked up in the microphone mixing and feed system. The buzz section also contained a large hum picked up from the power line. Therefore we could perform flutter sideband spectrum analysis on these hum recordings. The

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[1] Per mill = parts per thousand.

evidence tape was played back on a Nagra III recorder–reproducer.[2] The signal was then fed into a model UA-500 Ubiquitous® spectrum analyzer manufactured by Nicolet Scientific Corporation. The flutter sideband spectra were plotted on a Hewlett-Packard model 7035B *X–Y* graphic recorder.

We measured a typical flutter sideband spectrum from the 60-Hz hum signal on a speech portion of the evidence tape. This is shown in Fig. 1. Table I tabulates the significant flutter frequencies and amplitudes calculated from this spectrum of the speech section before the buzz.

Similarly, Figs. 2–5 show the flutter sideband spectra at various positions within the buzz section of the evidence tape. We calculated the major flutter frequencies and amplitudes, and these are also given in Table I.

The flutter sideband spectra, and the table of flutter spectra, show that the flutter spectra for the speech section of the evidence tape, and the following buzz section of the evidence tape, are quite different.

MECHANICAL ANALYSIS OF THE SONY AND UHER RECORDERS, MEASUREMENT OF THEIR FLUTTER SIDEBAND SPECTRA, AND CALCULATION OF THEIR FLUTTER SPECTRA

Sony 800B Recorders

Mechanical Analysis

The Sony 800B recorder uses a servo-controlled capstan motor whose shaft is itself the capstan that drives the tape. The capstan diameter is 4.0 mm. Thus with a tape speed of 24 mm/s, simple eccentricity produces a flutter frequency of 1.9 Hz, and ellipticity produces a flutter frequency of 3.8 Hz. The tape is driven by friction between the capstan and a freely rotating rubber pulley (capstan idler) whose diameter is 23.6 mm, producing a frequency of about 0.35 Hz for simple eccentricity.

The reel is driven by a belt-driven clutch whose frequency is 0.7 Hz. As tape winds off the reel, the tape pack radius varies from 54 to 23 mm. At the tape speed of 24 mm/s, the rotational speeds vary from 0.07 to 0.16 r/s, giving flutter frequencies from 0.07 to 0.16 Hz, corresponding to periods of 14.3 to 6.0 s.

Flutter Sideband Spectrum Measurement and Flutter Calculations

A 60-Hz tone from a Kron-Hite model 4100 oscillator was recorded onto blank tape by means of each of six Sony 800B's used in the Executive Office Building and in the Oval Office. The 60-Hz tone was recorded at a level corresponding to the midrange of the recording-level indicator on each machine. Then a flutter sideband spectrum analysis was performed by the means described in the preceding section. The spectra are shown in Figs. 6–11. The flutter frequencies and magnitudes have been calculated for these recorders and are shown in Table II.

Two points are worth a comment. First, the measured flutter frequencies correspond to the frequencies expected from the mechanical analysis, except for the one small unexplained flutter component at 1.25 Hz. Second, the flutter amplitude at each frequency is quite variable from one recorder to another.

Uher 5000 Recorders

Mechanical Analysis

The Uher 5000 uses an induction motor operating from the power line, driving an intermediate rubber idler, which in turn drives the flywheel that is on the capstan shaft. The motor operates at approximately 1740 r/s, giving a frequency of 29 Hz. The intermediate idler frequency is 3.6 Hz. The capstan diameter is 5.0 mm. Thus with a tape speed of 24 mm/s, simple eccentricity produces a flutter frequency of 1.5 Hz, and ellipticity produces a flutter frequency of 3.0 Hz. The capstan idler diameter is 21.8 mm, producing a frequency of 0.35 for simple eccentricity. As with the Sony, the reel is driven by a belt-driven clutch whose frequency is 0.7 Hz. The reel radii and frequencies are the same as those of the Sony since the same reel sizes are used on both machines in this work.

Flutter Sideband Spectrum Measurement and Flutter Calculations

The recording of tones and the sideband spectrum analysis were carried out as before on the Uher 5000's "Exhibit 60" and "Secret Service," and the spectra are shown in Figs. 12 and 13. The flutter frequencies and magnitudes have been calculated for these two recorders and are shown in Table III.

As with the Sony recorders, the frequencies correspond to those calculated by mechanical analysis, and the differences between the two individuals are rather large.

DETERMINING WHICH MODEL TAPE RECORDER RECORDED THE SPEECH AND THE BUZZ SECTIONS OF THE EVIDENCE TAPE

This section is predicated on the assumption discussed elsewhere that only Sony 800B and Uher 5000 recorders might have been used in recording and erasing the evidence tape.

Comparison of Sony and Uher Flutter Spectra

The capstan idlers on both the Sony and the Uher recorders produce 0.35-Hz flutter, and the reel-drive clutches both produce 0.7-Hz flutter. Therefore the amplitudes of these two components mean little in distinguishing Sony recordings from Uher recordings. The components at 1.4 and 1.5 Hz are characteristic of these recorders, but the noise background amplitude in the evidence tape makes it very difficult in this particular case to distinguish a 1.4-Hz component from a 1.5-Hz component. Therefore we will not consider the component amplitudes at 1.4 and 1.5 Hz.

The clearest differences between Sony and Uher flutter

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[2] Because of equipment limitations, and in order to save analysis time, the reproduction was performed at 95 mm/s (3.75 in/s), which is four times the original speed of the evidence tape, 24 mm/s (15/16 in/s). Thus the frequencies in analysis were all at four times their original values. For clarity of presentation, this note refers only to the original frequencies.

spectra are seen at 1.9 Hz (Sony capstan frequency) and at 3.6 Hz (Uher intermediate idler frequency). Table II shows that all the Sonys tested show appreciable flutter at 1.9 Hz and no flutter at 3.6 Hz. Table III shows that both Uhers tested show no flutter at 1.9 Hz and appreciable flutter at 3.6 Hz. Thus the flutter frequencies of 1.9 and 3.6 Hz should be examined in order to differentiate Sony recordings from Uher recordings.

Comparison of Flutter Spectra of the Speech and Buzz Sections of the Evidence Tape

Table I shows that the recording of the speech before the buzz section contains a large flutter component at 1.9 Hz and no flutter component at 3.6 Hz. These findings point to a Sony 800B. The amplitudes of the other components are consistent with those found in the Sony 800B flutter spectra

Table I. Flutter spectra from the evidence tape.

Frequency [Hz]	Flutter [per mill]				
		In Buzz Section			
	In Speech Section Before Buzz	Event at Time 1 s	Event at Time 50 s	Event at Time 275 s	Event at Time 1043 s
0.35	—	—	—	—	—
0.7	1.2	0.7	1.0	0.8	0.9
1.25	1.9	0.5	—	—	—
1.4	1.8	—	—	—	—
1.5	—	1.0	1.0	1.3	1.6
1.9	3.2	—	—	—	—
3.0	—	1.4	1.6	1.6	2.0
3.6	—	3.4	3.8	3.4	4.3
3.8	2.3	—	—	—	—
7.2	—	—	—	—	—
8.0	—	3.0	4.3	4.3	4.3

"—" indicates amplitude at this frequency is equal to the noise level at this frequency.

Table II. Flutter spectra from six Sony 800B recorders.

Frequency [Hz]	Mechanical Element	Flutter/[per mill]					
		EOB A SN 12 330	EOB B SN 15 367	EOB C SN 14 384	Oval Office SN 11 561	Oval Office SN 14 396	Oval Office SN 15 102
0.35	Capstan idler	—	0.4	0.4	—	—	—
0.7	Reel-drive clutch	0.5	1.3	0.7	0.9	0.9	0.6
1.25	?	0.3	0.3	0.3	—	—	0.5
1.4	2 × reel-drive clutch	0.4	0.4	—	—	0.4	0.4
1.5	None	—	—	—	—	—	—
1.9	Capstan	1.0	0.8	4.5	1.0	1.6	1.8
3.0	None	—	—	—	—	—	—
3.6	None	—	—	—	—	—	—
3.8	2 × capstan	—	—	—	1.9	—	1.2
7.2	None	—	—	—	—	—	—

"—" indicates amplitude at this frequency is equal to the noise level at this frequency

Table III. Flutter spectra from two Uher 5000 recorders.

Frequency [Hz]	Mechanical Element	Flutter/[per mill]	
		Secret Service	Exhibit 60
0.35	Capstan idler	0.9	—
0.7	Reel-drive clutch	0.4	0.7
1.25	None	—	—
1.4	2 × reel-drive clutch	—	—
1.5	Capstan	1.3	1.2
1.9	None	—	—
3.0	2 × capstan	—	1.4
3.6	Intermediate idler	3.0	4.8
3.8	None	—	—
7.2	2 × intermediate idler	1.8	1.9

"—" indicates amplitude at this frequency is equal to the noise level at this frequency.

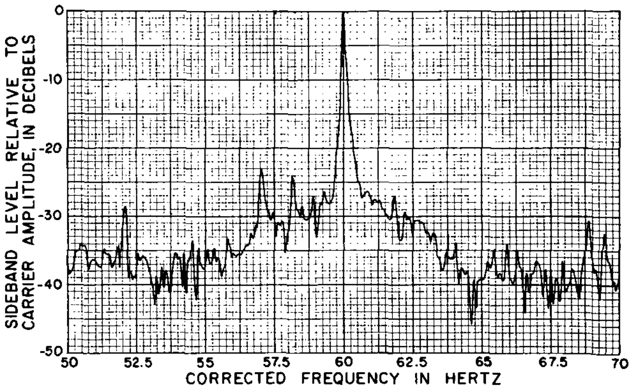

Fig. 1. Flutter sideband spectrum of hum in evidence tape speech recording before buzz section. Resolution, 0.05 Hz; average of two spectra, 20 s each; duration of signal analyzed, 40 s.

of Table II. Thus we conclude that the speech section was certainly recorded on a Sony 800B.

Table I also shows that the several recordings of the buzz all contain a large flutter component at 3.6 Hz and no component at 1.9 Hz. These point to a Uher 5000. The amplitudes of the other components are consistent with those found in the Uher 5000 flutter spectra of Table III. Thus we conclude that all the buzz section was certainly recorded on a Uher 5000.

DETERMINING WHICH SONY RECORDER RECORDED THE SPEECH SECTION

The flutter spectrum of the speech section of the evidence tape (Table I) may be compared with the flutter spectra of the six Sony 800B recorders in evidence (Table II). The flutter spectrum on the evidence tape contains 3.2 per mill of flutter at 1.9 Hz and 2.3 per mill at 3.8 Hz. The flutter spectra of the six Sony 800B recorders do not contain these amplitudes at these frequencies. On the basis of this

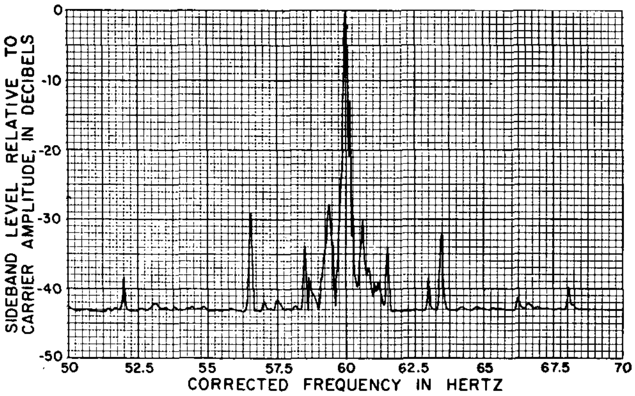

Fig. 2. Flutter sideband spectrum of buzz in evidence tape buzz section beginning at event time 1 s. Resolution, 0.05 Hz; average of two spectra, 20 s each; duration of signal analyzed, 40 s.

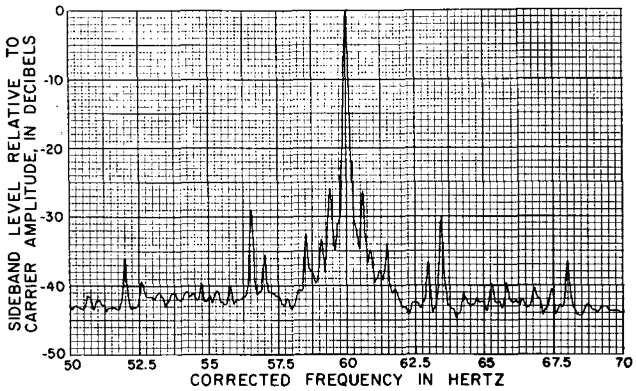

Fig. 3. Flutter sideband spectrum of buzz in evidence tape buzz section, beginning at event time 50 s. Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

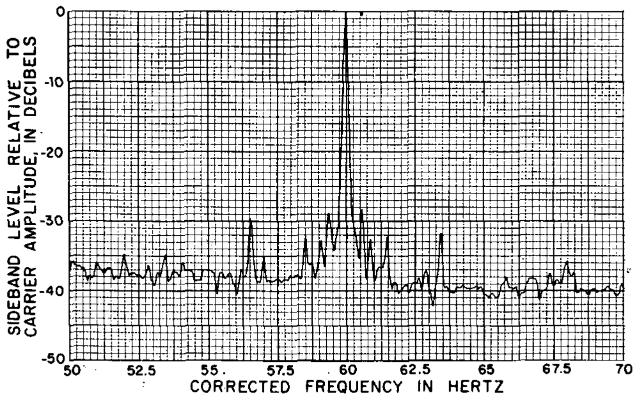

Fig. 4. Flutter sideband spectrum of buzz in evidence tape buzz section, beginning at event time 276 s. Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

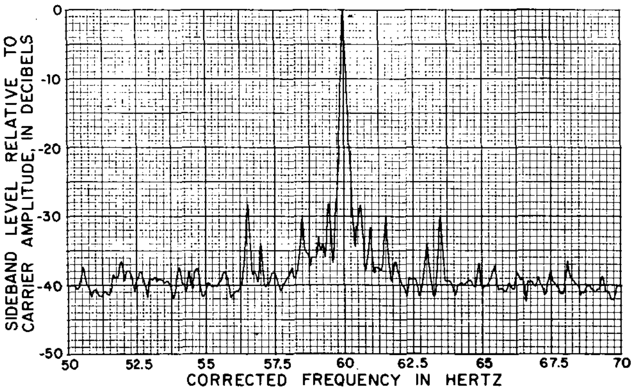

Fig. 5. Flutter sideband spectrum of buzz in evidence tape buzz section, beginning at event time 1043 s. Resolution, 0.05 Hz; average of two spectra, 20 s each; duration of signal analyzed, 40 s.

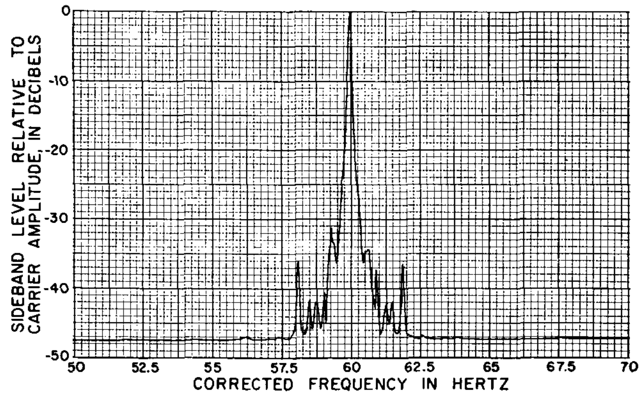

Fig. 6. Flutter sideband spectrum of a 60-Hz test recording from Sony 800B recorder SN 12 330, "EOB A." Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

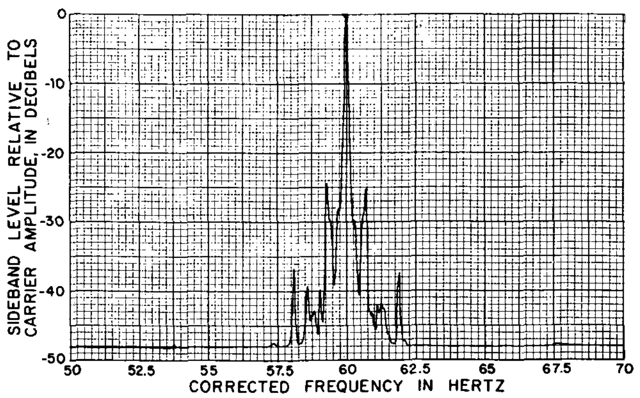

Fig. 7. Flutter sideband spectrum of a 60-Hz test recording from Sony 800B recorder SN 15 367, "EOB B." Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

evidence we must conclude that although the speech section of the evidence tape was certainly recorded on some Sony 800B, it was not one of the Sonys that was tested.

DETERMINING WHICH UHER RECORDER RECORDED THE BUZZ SECTION

The flutter spectra of the several parts of the buzz section of the evidence tape (Table I) may be compared with the flutter spectra of the two Uher 5000 recorders in evidence (Table III). For ease of comparison, the critical frequencies are retabulated in Table IV. Inspection of this table shows a good correlation at all the critical frequencies between the flutter spectrum of the buzz section and that of the Uher "Exhibit 60." The correlation with the Secret Service Uher is not at all good. We therefore conclude that, given these two Uher 5000 recorders, the buzz section was very likely recorded on the Uher 5000 "Exhibit 60."

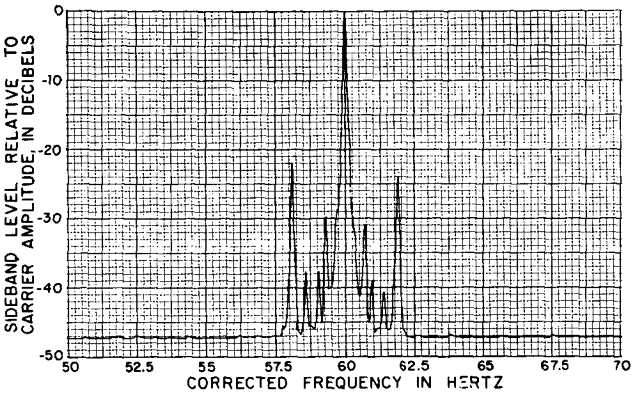

Fig. 8. Flutter sideband spectrum of a 60-Hz test recording from Sony 800B recorder SN 14 384, "EOB C." Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

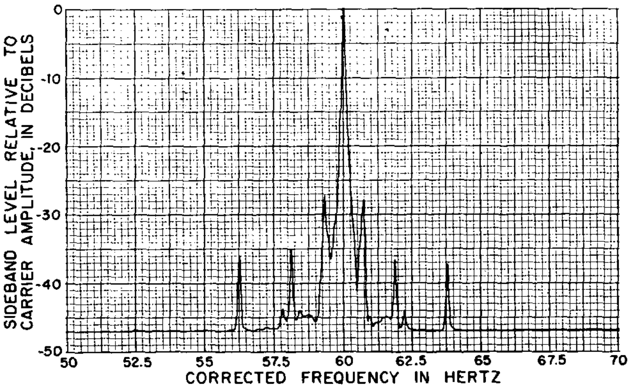

Fig. 9. Flutter sideband spectrum of a 60-Hz test recording from Sony 800B recorder SN 11 561, "Oval Office." Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

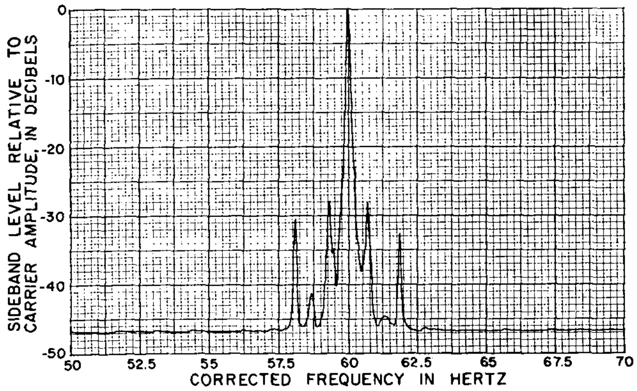

Fig. 10. Flutter sideband spectrum of a 60-Hz test recording from Sony 800B recorder SN 14 396, "Oval Office." Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

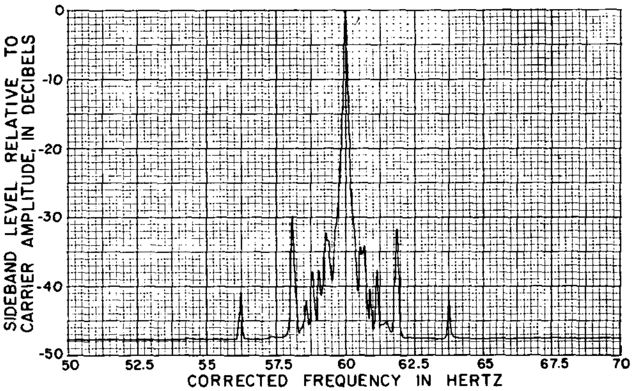

Fig. 11. Flutter sideband spectrum of a 60-Hz test recording from Sony 800B recorder SN 15 102. "Oval Office." Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

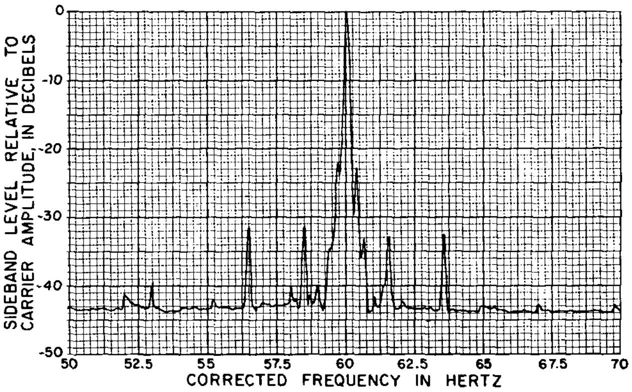

Fig. 12. Flutter sideband spectrum of a 60-Hz test recording from Uher 5000 recorder labeled "Secret Service." Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

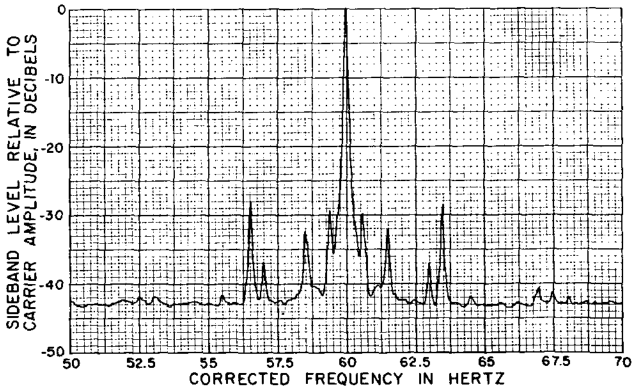

Fig. 13. Flutter sideband spectrum of a 60-Hz test recording from Uher 5000 recorder labeled "Exhibit 60." Resolution, 0.05 Hz; average of eight spectra, 20 s each; duration of signal analyzed, 160 s.

Table IV. Comparison of critical frequencies in the flutter spectra of two Uher recorders and the buzz section.

Frequency [Hz]	Flutter/[per mill]						
	Tape Recorder		Part of Buzz Section				
	Secret Service	Exhibit 60	Average of 4	Event at Time 1 s	Event at Time 50 s	Event at Time 275 s	Event at Time 1043 s
0.35	0.9	—	—	—	—	—	—
0.7	0.4	0.7	0.9	0.7	1.0	0.8	0.9
3.0	—	1.4	1.7	1.4	1.6	1.6	2.0
3.6	3.0	4.8	3.7	3.4	3.8	3.4	4.3

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THE AUTHORS

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He received a Bachelor of Science degree in electrical engineering at Stanford University in 1952. Upon graduation, he joined Ampex Corporation where he was involved in the design and development of audio tape recorders. While serving in the U.S. Army from 1953-56, Mr. McKnight worked as an operator of sound-recording equipment in the Armed Forces Radio Service Studio in New York City. He returned to Ampex Corporation in 1956 and served in a number of the company's divisions before becoming a private consultant in 1972. While at Ampex, Mr. McKnight was involved in many aspects of research, engineering, and design related to magnetic tape recording systems and their elements. He is the author of more than forty technical papers and presentations. He is also a principal author of standards on audio flutter measurement and tape flux measurement published by the American National Standards Institute.

He is a member of numerous national and international sound-recording standards committees. A Senior Member of the Institute of Electrical and Electronics Engineers since 1962, Mr. McKnight served on the administrative committee of that Society's Group on Audio and Electroacoustics and its standards committee. He is a Fellow of the Audio Engineering Society, a member of the AES Editorial Board, past chairman of the AES Standards Committee, and he has twice served as Governor of the Society. In 1971 Mr. McKnight received the AES Award "for outstanding services in furthering theory and practice of magnetic recording . . . ."

He was also a member of the Advisory Panel on White House Tapes in 1973-74.

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He has conducted and directed research aimed at the development of analog instruments and digital computer techniques for the analysis, classification, and processing of a variety of audio signals. Much of his work centered on the use of instruments and instrumentation techniques for spectrum analysis of acoustic waveforms. His major interest is in the development of methods for analyzing speech and for increasing the detectability and intelligibility of speech that is obscured by noise.

Mr. Weiss has a B.E.E. from the City College of New York, and an M.S. in electrical engineering from Columbia University. He is a Fellow of the Acoustical Society of America, a member of the Institute of Electrical and Electronics Engineers, and a member of Eta Kappa Nu. He is the author or co-author of two dozen papers and reports, most of them in the field of speech research.