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(54) ACTIVE ACOUSTIC TRANSMISSION LOSS BOX

Gehäuse mit aktiv erzeugtem akustischem Übertragungsverlust

CAISSON ACTIF REDUISANT LA TRANSMISSION ACOUSTIQUE

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(73) Proprietor: **NCT Group, Inc.**
Linthicum, MD 21090-1206 (US)

(72) Inventors:
- **FULLER, Chris**
  Blacksburg, VA 24060 (US)
- **McLOUGHLIN, Michael**
  Sykesville, MD 21784 (US)
- **HILDEBRAND, Steve**
  Arlington, VA 22202 (US)

(74) Representative: **Stone, Patrick**
28 Edenside Drive
Attleborough Norfolk NR17 2EL (GB)

(56) References cited:

EP-A- 0 083 718	WO-A-81/01479
US-A- 2 776 020	US-A- 3 602 331
US-A- 4 025 724	US-A- 4 689 821
US-A- 4 815 139	US-A- 5 091 953

- **IBM Technical Disclosure Bulletin, Volume 31, No. 8, January 1989, "Audible Noise Suppression", see page 256, third paragraph, and page 257, third paragraph.**

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EP 0 664 044 B1

Description

Background of the Invention

[0001] The present invention relates generally to noise or sound control and more particularly to the control of radiated sound from vibrating machinery by enclosing the machinery in what is termed an "active box or container". The purpose of the active box is to markedly reduce the radiation of the sound from the machine to observation points in the surrounding field, with a very lightweight, compact, non-airtight structure.

Discussion of Related Art

[0002] In many applications the radiation of sound from vibrating machines is an annoying noise problem. One technique which has been used in the past is to enclose the machine in a high transmission loss (TL) box in order to reduce the radiated sound (as described, for example, in U.S. Patent No. 4,715,599, hereby incorporated by reference herein and in "Noise and Vibration Control" by L. Beranek, 1988). These conventional boxes attenuate the sound transmitted through their walls by passive means. In order that the container be effective, i.e. strongly reduce the sound, it has to be both airtight and constructed from material which has a high density and thickness. These two conditions have a number of practical disadvantages. For example, the airtight condition implies that it would be extremely difficult to build an effective high TL container for applications which require air flow (e.g. a.c. units, compressors, etc.) or piping and wiring connections or ventilation for cooling. These requirements would imply significant holes through which the acoustic energy could leak. The high density material condition of course would imply that the box be extremely heavy and large in size, a problem which is exacerbated as the frequency of sound becomes lower.

[0003] Previous work has shown the extremely high potential of using active vibration inputs to structures to reduce the radiated sound from the structural vibration. Such work is described in "Apparatus and Method for Global Noise Control", U.S. Patent No. 4,715,599, 1987, by C. R. Fuller and "Control of Sound Radiation with Adaptive Structures", Journal of Intelligent Material Systems and Structures, Vol. 2, pp. 431-452, 1991, by R. L. Clark and C. R. Fuller. The control inputs can be in the form of point force shakers or surface strain devices, such as piezoelectric elements, bonded to the surface of the structure. In order that the control approach be efficient and effective, the variable to be minimized has to be the radiated sound from the panel, measured, for example, by error microphones located in the radiated sound field as in Fuller. The controller format can be any control approach which adjusts the oscillating voltage inputs to the piezoelectric inputs, for example, in order to minimize the radiated sound observed at the error microphones. Polyvinylidene fluoride (PVDF) piezoelectric distributed sensors on the surface of a panel have been used in place of microphones to sense modes of the panel which are radiating efficiently to the far field such as that described in "Modal sensing of efficient acoustic radiators with polyvinylidene fluoride distributed sensors in active structural acoustic control approaches", J. Acoustical Society of America, pp 3321-3329, June 1992, by Clark and Fuller. The work of Clark and Fuller, for example, demonstrates attenuations of the order of 20 dB of sound radiated from panels in the low frequencies ($f \leq 600$ Hz) with only one or two active actuator inputs.

[0004] From European Patent Specification No. 0 083 718 is known an active noise reduction system having sound insulation panels at least partly enclosing a noise source constituted by an oil-filled induction apparatus, actuator means generating in the enclosure panels vibrations to cancel the noise from the source, and error sensing means detecting the noise in the panels and providing error signals to a controller means for the actuator means. No account is taken of noise in the far field outside the tank of the induction apparatus and the controller means does not specifically take into account temporal characteristics of the noise source such as frequency.

[0005] Again, in the context of an oil-filled transformer tank giving rise to transformer hum, Patent Specification No. WO 81/01479 is provided with a reference signal or waveform generator which controls a vibrator for injecting noise cancellation signals into the oil. Sensing means for feeding signals to the generator are located on the transformer tank. Again, no account is taken of noise present in the far field outside the transformer tank.

[0006] It is accordingly an object of the present invention to provide an improved system and method of general applicability for achieving high attenuation of radiated sound from a vibrating machine by enclosing it with a structural container means which forms an active acoustic transmission loss box.

[0007] According to one aspect of the invention, there is provided an active noise reduction system as defined by the appended claim 1.

[0008] According to another aspect of the invention, there is provided a method of controlling noise radiation as defined by the appended independent claim 12.

[0009] In the accompanying drawings:-

[0010] Figure 1 is a schematic of a typical box (in this case rectangular) surrounding a noisy machine. The active inputs, error microphones and PVDF film as discussed above are shown. Also demonstrated is an air gap in the box side wall.

[0011] Figure 1 is a typical general controller arrangement used to derive the correct active control signal, using microphones as error sensors.

[0012] Figure 3 is a typical general controller arrangement used to derive the correct active control signal using PVDF film as an error sensor.

[0013] Figure 4 is a schematic of the use of panels to surround a noisy structure.

[0014] Figure 5 is an azimuth plot of typical noise radiation from an enclosure with and without active control.

[0015] Figure 6 shows a typical noise spectrum at a selected error microphone with and without control. This result shows control of broadband or multiple frequencies simultaneously.

[0016] Referring now to the drawings, an example configuration of the active acoustic transmission loss box is shown in Figure 1 as 10. A machine 11 is operating and radiating unwanted noise inside the box. The machine requires some air flow for cooling etc. as well as piping and electrical connections and an air gap 23 can be provided. In order to control the sound radiation the machine is surrounded by an enclosure, in this case a rectangular box 12. In the example of Figure 1, the box 12 is resting on the machine support base 13 but also could totally surround it. Damping or absorptive materials can also be added to the box to attenuate high frequency noise and improve the structural response of the enclosure. The box can be constructed from a variety of materials such as thin steel, aluminum, etc. In the case shown the box is manufactured from 6.35 mm plexiglass and has dimensions 304.8 x 304.8 x 406.4 mm. Piezoceramic control actuators such as 13, 14, 15 (type G1195 of thickness 0.19 mm and dimensions 38.1 x 63.5 mm) are bonded to the center of each panel. Each actuator consists of a piezoceramic element bonded onto each side, co-located and wired in parallel with 180° phase shift. Such a configuration produces high vibration of the panels. These elements can be positioned in various arrays and also embedded in the material if required.

[0017] In order to sense the radiated noise field, a number of error microphones such as 16, 17, 18 are positioned in the radiated noise field. The number and location of the error microphones is dependent upon the modal contribution (from the panel vibration) and radiation directivity of the noise. A controller 19 is employed which measures the output of the error microphones and then constructs an oscillating control signal of the correct frequency content and phase which, when fed to the control actuators 13, 14, 15, etc. causes the sound to be markedly reduced at the error microphones and other locations. An alternative to microphones is PVDF thin film which can be placed on the walls in such a way that energy in the radiating modes is sensed. One possible configuration for the PVDF strips such as 20, 21, 22 is shown in Figure 1. Another alternative would be to use accelerometers to sense the motion of specific points on the enclosure walls.

[0018] One particular control arrangement embodies the Filtered-X adaptive LMS algorithm discussed by Fuller. An oscillating reference signal which has the frequency content of the noise to be canceled is taken from machine 50. This reference signal 51 is also highly coherent with the output of the error microphones. The reference signal is passed through an analog to digital (A/D) converter 52 and fed through a number of adaptive filter 53. The number of adaptive filters is equal to the number of control actuators used. The arrangement of the adaptive filter is dependent upon the frequency content of the noise. The outputs of the adaptive filters is then passed through D/A converters 54 and smoothing filters 55. For piezoceramic actuators 57, this control signal is typically passed through a high voltage power amplifier and then connected to the electrodes of each actuator. The error signals from the microphones 56 are sampled using A/D converters and then used in conjunction with the reference signal and a filtered-X update equation in the controller 61 in order to adapt or change the coefficients of the adaptive filters so as to minimize the error signals from the microphones as far as possible.

[0019] In an experimental arrangement to test the performance of such a system the noisy machine is replaced with a 165.1 mm speaker 58 positioned in a 184.2 m x 184.2 m x 114.3 m reflex box. Various test frequencies are then fed to the speaker to generate noise. The reference signal 51a in this case is taken directly from the signal 59 driving the speaker. For this test the control actuators on diametrically opposite panels were wired in phase, creating in conjunction with a top actuator 60, three independent control channels and hence three adaptive filters. Three error microphones such as 56 were positioned at a distance of approximately 2 m from the box. In this arrangement the air gap 23 shown in Figure 1 is approximated by raising the box of 254 mm blocks at each corner thus leaving a total air gap of 361.2 cm^2, giving a percentage open area in the box of 6.5%.

[0020] Figure 5 shows a typical radiation directivity pattern measured around the box at mid plane and a distance of 1.7m. The curve 90 labeled "control off" gives the radiated noise field without any enclosure. The curve 91 "control on" gives the radiated noise field when the box is in place but the control is not activated. It is apparent that the box only provides a small attenuation of the sound. When the control is turned on, the results of Figure 6, labeled "with control" show high sound reductions of the order of 20 dB at all angles (i.e. global control).

[0021] As discussed by Fuller in Patent No.4,715,599 the active attenuation is achieved as follows. The noise source inside the box radiates sound which strikes the enclosure walls and causes it to vibrate (at the same frequency content as the noise source). The vibrating walls then radiate sound away to the exterior free field of the box where it appears as unwanted noise. The active inputs work as follows. The structural actuators cause anti-vibration in the walls of the enclosure. When the inputs to the structural actuators are adjusted correctly these anti-vibrations cancel out those vibrations in the box which were previously radiating sound, thus leading to global sound reduction. As in Fuller's patent, not all vibrations (or modes) in the enclosure will radiate sound and thus the active inputs need only cancel those vibrations (or modes) that are efficient radiators rather than controlling all the vibration. This approach leads to a very low number of control actuators as opposed to totally canceling the box vibration, and is the key to the success of the approach.

[0022] An alternative, shown in Figure 4, is to enclose the noisy structure 80 with close fitting panels 85 instead of a free standing enclosure. In this case the enclosure panels are attached directly to the sides of the noise source. If the regions generating noise are localized or if noise control is needed in certain directions, an advantage to this method is that the need to enclose the entire structure is eliminated. In addition, in many cases a more compact enclosure can be constructed without restricting airflow needed for cooling. An example of an application of this method would be for the reduction of "hum" from electrical transformers. Transformer noise is generated from magnetostrictive forces in the coil and are propagated to the transformer skin through the oil field and coil foundation.

[0023] Figure 4 shows a cancellation system 80 for enclosing a noisy structure with close fitting panels. Controller 81 receives a reference signal 82 from the structure and inputs 83, from error microphone 84. Actuators 86 are located on close fitting panels 85.

[0024] Still another alternative shown in Figure 3 is to place the actuator directly on the surface of the noise source.

[0025] Figure 3 shows noise reduction system 70 with active structural control provided with a Noise Cancellation Technologies, Inc. controller 71 and power amplifier 72 having outputs to piezoceramic actuators such as 73, 74 and inputs from PVDF sensor film strips such as 75, 76, 77.

[0026] An alternative to using structural actuators to anti-vibrate the enclosure walls is to use loudspeakers to generate a pressure field inside the box that will produce the anti-vibrations. Combinations of different sensors such as and microphones can also be used.

[0027] Having described the invention in detail it will be obvious to those of ordinary skill in the art that changes can be made without departing from the scope of the appended claims which define the invention.

Claims

1. An active noise reduction system for cancelling a noise disturbance emanating from a source of noise, said system comprising

   a structural container means (12) at least partially surrounding the noise source and having a plurality of actuator means (13, 14, 15) attached thereto to cause the container means to vibrate and generate anti-vibrations, and
   a plurality of error sensing means (16, 17, 18) adapted to detect noise radiation and provide error signals, and a controller means (19) comprising circuit means connected to the error sensing means and for controlling the actuator means to generate said anti-vibrations,

   characterised in that a reference signal generator is provided to supply the controller means with frequency and temporal information on the noise disturbance, in that the error sensors are adapted to detect radiated noise in the far-field outside the container means, and in that the controller means independently controls each actuator means dependently on both the error signals and the reference signal (51) supplied to said controller means to drive the error signals to minimum values simultaneously.

2. The system of claim 1 wherein said structural container means (12) has an air gap (23) therein.

3. The system of claim 1 wherein said structural container means has wall means adapted to be close fitting to said noise disturbance.

4. The system of claim 1 or claim 2 or claim 3 wherein said actuator means are piezoceramic actuator means (13, 14, 15).

5. The system of claim 4 wherein said actuator means are embedded piezoceramic actuators.

6. The system of claim 4 wherein said actuator means are surface mounted piezoceramic actuators.

7. The system of claim 1 or claim 2 or claim 3 wherein said actuator means are electrodynamic shakers.

8. The system of claim 1 or claim 2 or claim 3 wherein said actuator means are loudspeaker means.

9. The system of any of claims 1 to 8 wherein said error sensing means are PVDF film (20, 21, 22).

10. The system of any of claims 1 to 8 wherein said error sensing means are microphones (16, 17, 18).

11. The system of any of claims 1 to 8 wherein said error sensing means are hydrophones.

12. A method of controlling noise radiation from a noise source by at least partly enclosing the source in a noise-reducing container, wherein a plurality of error sensing means detect noise radiation and supply error signals to a controller means which de-

pendently on said error signals supplies drive signals to a plurality of actuator means for vibrating the noise-reducing container to generate anti-vibrations, characterised by the steps of (1) sensing the far-field radiation outside the container by means of the plurality of error sensing means; (2) generating a reference signal containing frequency and temporal content of noise source; (3) feeding both the error signals and the reference signal to the controller means; and (4) controlling the sound radiation at the plurality of error sensing means by adjusting oscillating inputs supplied by the controller means to the plurality of actuator means in accordance with a control law to drive the error signals to minimum values simultaneously.

Patentansprüche

1. Aktives Geräuschreduziersystem zum Aufheben einer aus einer Geräuschquelle stammendnen Geräuschstörung, mit

   einem Baubehälter (12), der die Geräuschquelle zumindest teilweise umgibt und
   eine Mehrzahl von Ansprechvorrichtungen (13, 14, 15) aufweist, die damit verbunden sind, und die bewirken, daß der Baubehälter in Vibrationen versetzt wird und Gegenvibrationen erzeug,
   einer Mehrzahl von Fehlerfeststellvorrichtungen bzw. Fehlersensoren (16, 17, 18), die in der der Lage sind, eine Geräuschstrahlung zu detektieren und Fehlersignale zu erzeugen, und
   einer Steuervorrichtung (19), die eine Schaltung aufweist, welche mit der Fehlerfeststellvorrichtung verbunden ist und die Ansprechvorrichtung zur Erzeugung der Gegenvibrationen steuert,

   dadurch gekennzeichnet, daß ein Bezugssignalgenerator vorgesehen ist, um die Steuervorrichtung mit Frequenz- und Zeit-Informationen über die Geräuschstörung zu speisen, daß die Fehlersensoren in der Lage sind, abgestrahlte Geräusche in weiter abgelegenen Außenbereichen des Baubehälters zu detektieren, und daß die Steuervorrichtung jede Ansprechvorrichtung unabhängig steuert, und zwar sowohl in Abhängigkeit von den Fehlersignalen als von dem Bezugssignal (51), das in die Steuervorrichtung eingespeist wird, um die Fehlersignale gleichzeitig auf Minimumwerte zu bringen.

2. System nach Anspruch 1, bei dem der Baubehälter (12) einen Luftspalt (23) aufweist.

3. System nach Anspruch 1, bei dem der Baubehälter eine Wand besitzt, die mit enger Toleranz an die Geräuschstörung angepaßt ist.

4. System nach Anspruch 1, 2 oder 3, bei der die Ansprechvorrichtung aus piezokeramischen Ansprechelementen bzw. Ansprechgeräten (13, 14, 15) besteht.

5. System nach Anspruch 4, bei dem die Ansprechvorrichtung aus eingebetteten piezokeramischen Ansprechelementen besteht.

6. System nach Anspruch 4, bei dem die Ansprechvorrichtung aus an der Oberfläche befestigten piezokeramischen Ansprechelementen besteht.

7. System nach Anspruch 1, 2 oder 3, bei dem die Ansprechvorrichtung aus elektrodynamischen Rüttlern besteht.

8. System nach Anspruch 1, 2 oder 3, bei dem die Ansprechvorrichtung aus Lautsprechern besteht.

9. System nach einem der Ansprüche 1 - 8, bei dem die Fehlerfeststellvorrichtung ein PVDF-Film (20, 21, 22) ist.

10. System nach einem der Ansprüche 1 - 8, bei dem die Fehlerfeststellvorrichtung Mikrophone (16, 17, 18) aufweist.

11. System nach einem der Ansprüche 1 - 8, bei dem die Fehlerfeststellvorrichtung Hydrophone aufweist.

12. Verfahren zum Steuern von Geräuschstrahlungen aus einer Geräuschquelle, die zumindest teilweise in einem Geräusche reduzierenden Baubehälter eingeschlossen ist, wobei eine Mehrzahl von Fehlerfeststellvorrichtungen Geräuschstrahlungen detektieren und Fehlersignale in eine Steuervorrichtung einspeisen, die in Abhängigkeit von diesen Fehlersignalen Antriebssignale an eine Mehrzahl von Ansprechvorrichtungen gibt, um den die Geräusche reduzierenden Baubehälter in Vibrationen zu versetzen und Gegenvibrationen zu erzeugen, dadurch
gekennzeichnet, daß

   a) die weiter weg liegende Strahlung außerhalb des Baubehälters mit Hilfe der Mehrzahl von Fehlerfeststellvorrichtungen festgestellt wird,
   b) ein Bezugssignal erzeugt wird, das einen Frequenz- und Zeitanteil der Geräuschquelle enthält,
   c) sowohl die Fehlersignale als auch das Bezugssignal in das Steuergerät eingeführt werden, und
   d) die Schallstrahlung an der Mehrzahl von

Fehlerfeststellvorrichtungen durch Einstellen von oszillierenden Eingängen gesteuert wird, die durch die Steuervorrichtung in die Mehrzahl von Ansprechvorrichtungen nach einer Gesetzmäßigkeit eingespeist werden, um die Fehlersignale gleichzeitig auf minimale Werte zu bringen.

Revendications

1. Système actif de réduction de bruit pour annuler une perturbation bruyante émanant d'une source de bruit, ledit système comportant

   des moyens formant enceinte structurelle (12) entourant au moins partiellement la source de bruit et ayant une pluralité de moyens actionneurs (13, 14, 15) fixés à ceux-ci pour amener les moyens formant enceinte à vibrer et produire des anti-vibrations, et
   une pluralité de moyens de détection d'erreurs (16,17,18) adaptés pour détecter un rayonnement de bruit et délivrer des signaux d'erreurs, et des moyens contrôleurs (19) comportant des moyens de circuit connectés aux moyens de détection d'erreurs et destinés à amener les moyens actionneurs à produire lesdites anti-vibrations,

   caractérisé en ce qu'un générateur de signal de référence est prévu pour alimenter les moyens contrôleurs en informations temporelles et de fréquence concernant la perturbation bruyante, en ce que les détecteurs d'erreurs sont adaptés pour détecter un bruit irradié dans le champ lointain à l'extérieur des moyens formant enceinte, et en ce que les moyens contrôleurs commandent de manière indépendante chacun des moyens actionneurs en fonction à la fois des signaux d'erreurs et du signal de référence (51) délivrés dans lesdits moyens contrôleurs afin d'amener simultanément les signaux d'erreurs à des valeurs minimales.

2. Système selon la revendication 1, dans lequel lesdits moyens formant enceinte structurelle (12) ont une entrée d'air (23) à l'intérieur.

3. Système selon la revendication 1, dans lequel lesdits moyens formant enceinte structurelle ont des moyens formant parois adaptés pour être ajustés de manière précise à ladite perturbation bruyante.

4. Système selon la revendication 1, 2 ou 3, dans lequel lesdits moyens actionneurs sont des moyens actionneurs piézo-céramiques (13, 14, 15).

5. Système selon la revendication 4, dans lequel lesdits moyens actionneurs sont des actionneurs piézo-céramiques encastrés.

6. Système selon la revendication 4, dans lequel lesdits moyens actionneurs sont des actionneurs piézo-céramiques montés en surface.

7. Système selon la revendication 1, 2 ou 3, dans lequel lesdits moyens actionneurs sont des vibreurs électrodynamiques.

8. Système selon la revendication 1, 2 ou 3, dans lequel lesdits moyens actionneurs sont des moyens de haut-parleur.

9. Système selon l'une quelconque des revendications 1 à 8, dans lequel les moyens de détection d'erreurs sont constitués d'un film de PVDF (20, 21, 22).

10. Système selon l'une quelconque des revendications 1 à 8, dans lequel lesdits moyens de détection d'erreurs sont des microphones (16, 17, 18).

11. Système selon l'une quelconque des revendications 1 à 8, dans lequel lesdits moyens de détection d'erreurs sont des hydrophones.

12. Procédé de commande d'un rayonnement de bruit provenant d'une source de bruit en enfermant au moins partiellement la source dans une enceinte de réduction de bruit, dans laquelle une pluralité de moyens de détection d'erreurs détectent un rayonnement de bruit et délivrent des signaux d'erreurs dans des moyens contrôleurs qui, conformément auxdits signaux d'erreurs, délivrent des signaux d'entraînement dans une pluralité de moyens actionneurs pour faire vibrer l'enceinte de réduction de bruit afin de produire des anti-vibrations, caractérisé par les étapes consistant à (1) détecter le rayonnement en champ lointain à l'extérieur de l'enceinte par l'intermédiaire de la pluralité de moyens de détection d'erreurs, (2) produire un signal de référence comportant le contenu temporel et de fréquence de la source de bruit, (3) envoyer à la fois les signaux d'erreurs et le signal de référence dans les moyens contrôleurs, et (4) commander le rayonnement sonore au niveau de la pluralité des moyens de détection d'erreurs en ajustant des entrées oscillantes délivrées par les moyens contrôleurs dans la pluralité de moyens actionneurs conformément à un principe de commande pour amener simultanément les signaux d'erreurs à des valeurs minimales.

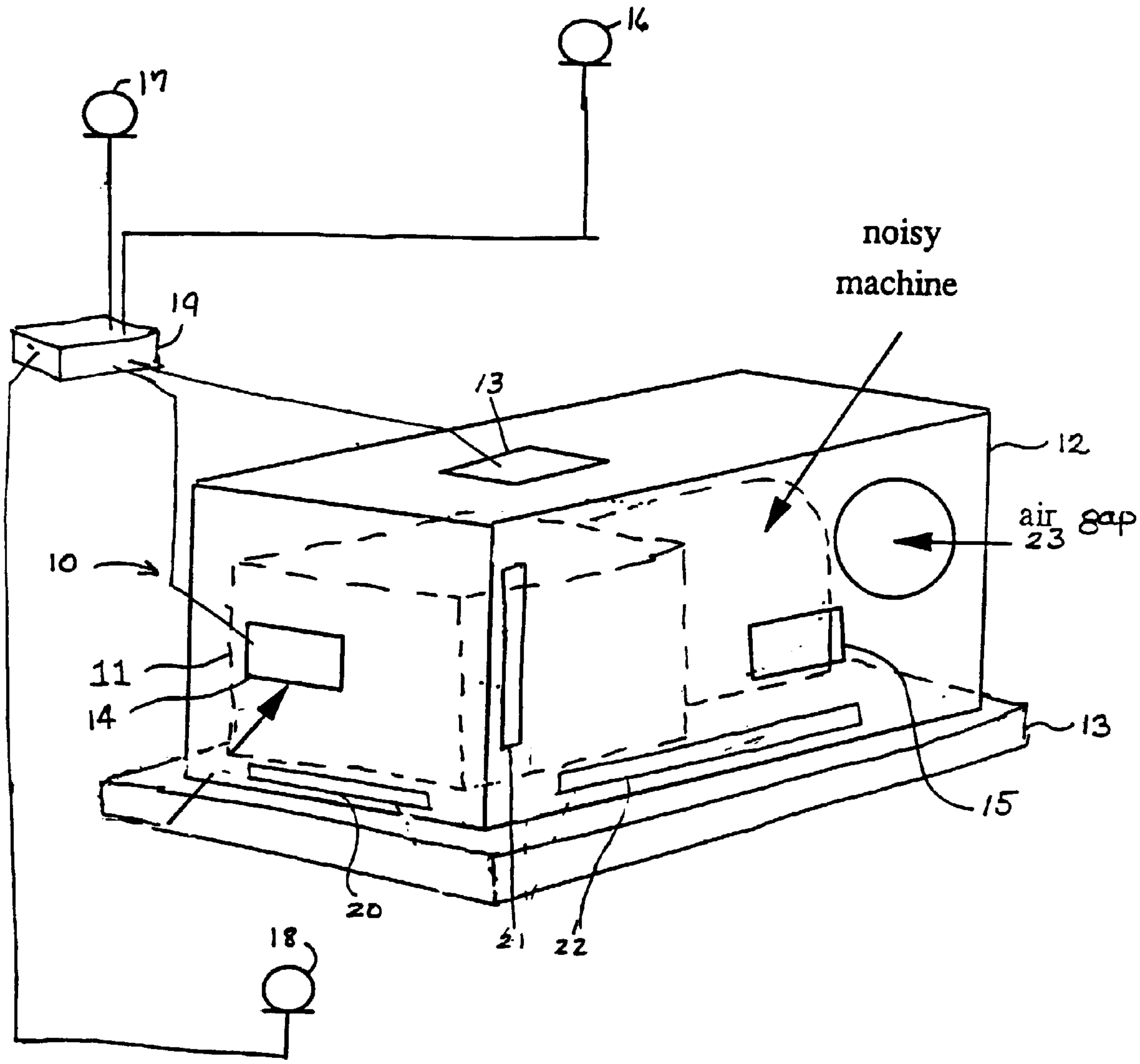


FIG 1

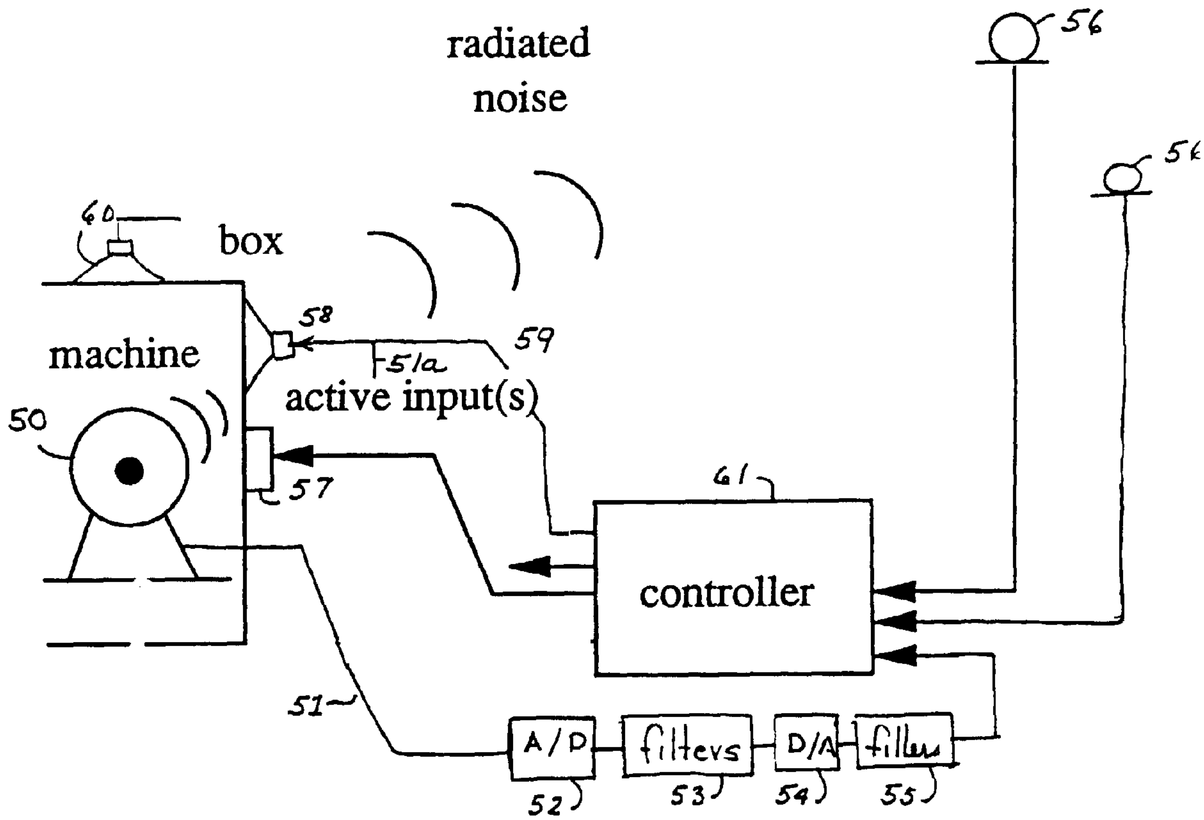

radiated
noise
56
56
60
box
machine
58
59
51a
active input(s)
50
57
61
controller
51
A/D
filters
D/A
filter
52
53
54
55

FIG 2

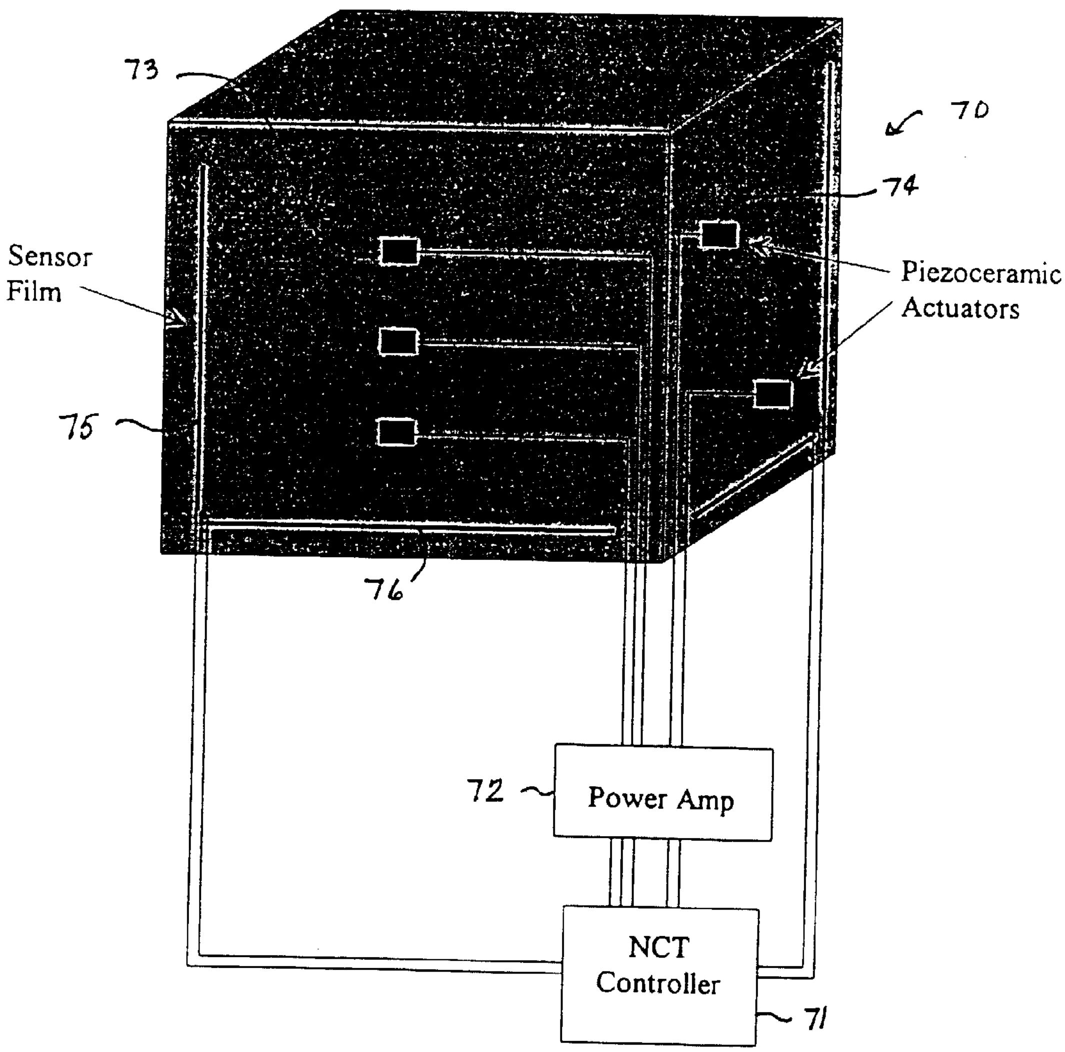

73
70
74
Sensor
Film
Piezoceramic
Actuators
75
76
72
Power Amp
NCT
Controller
71

FIG 3

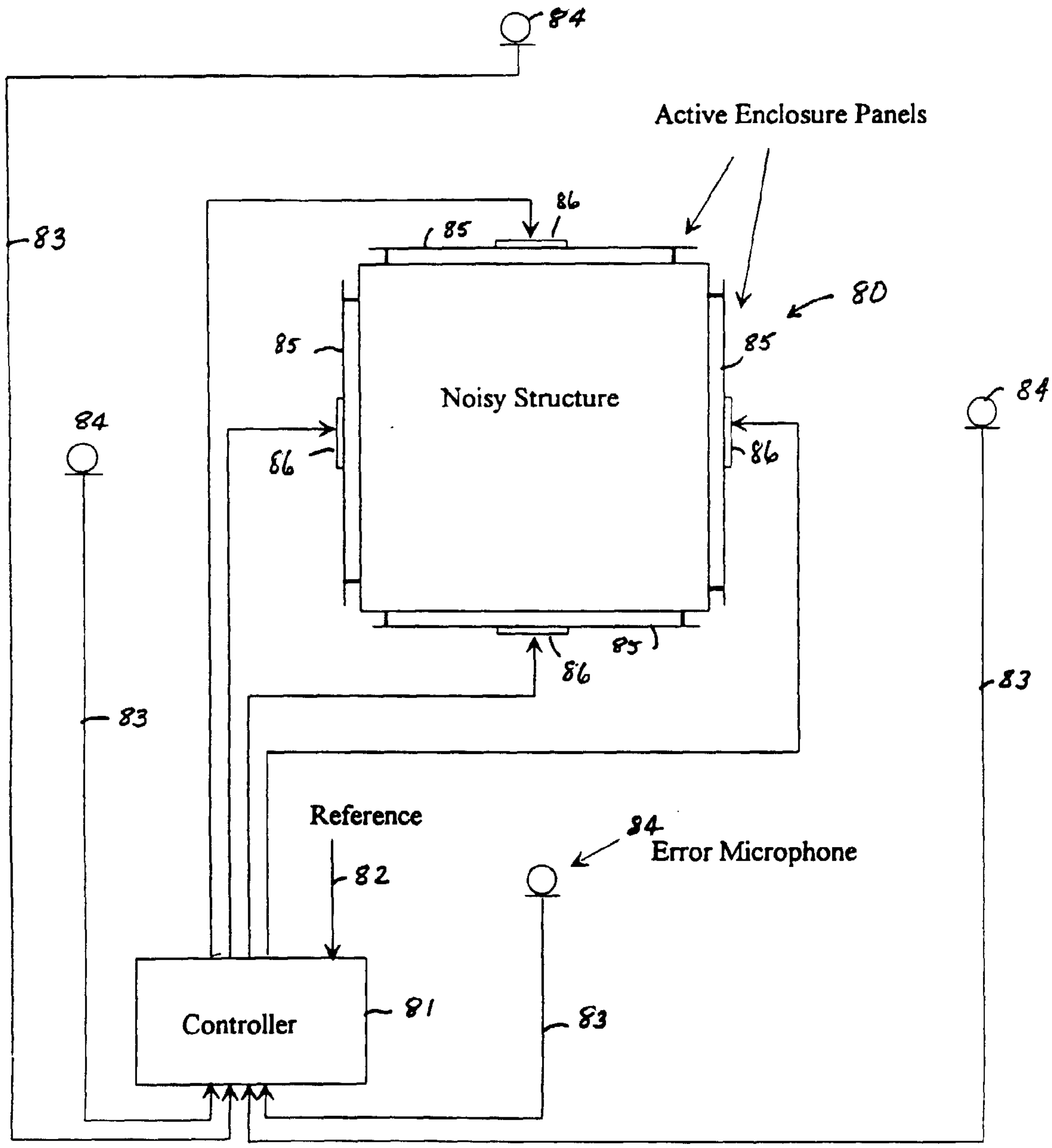

84
Active Enclosure Panels
86
85
83
80
85
85
Noisy Structure
84
84
86
86
85
86
83
83
Reference
84
Error Microphone
82
Controller
81
83

Figure 4

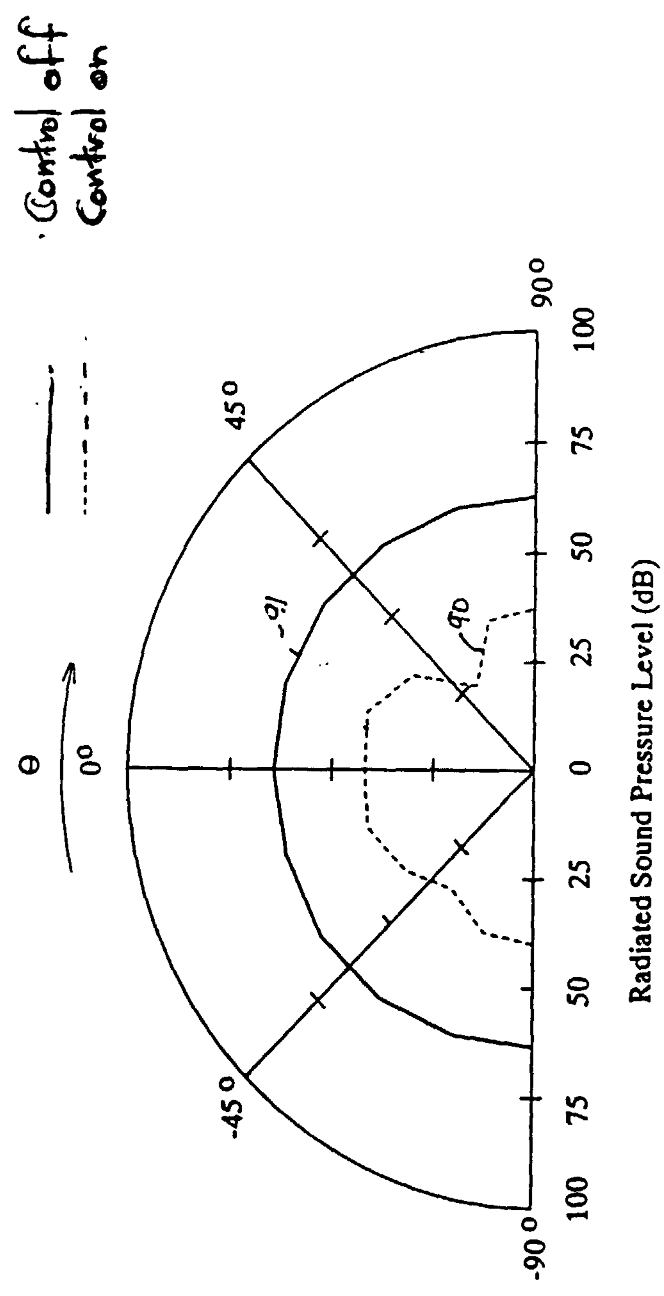
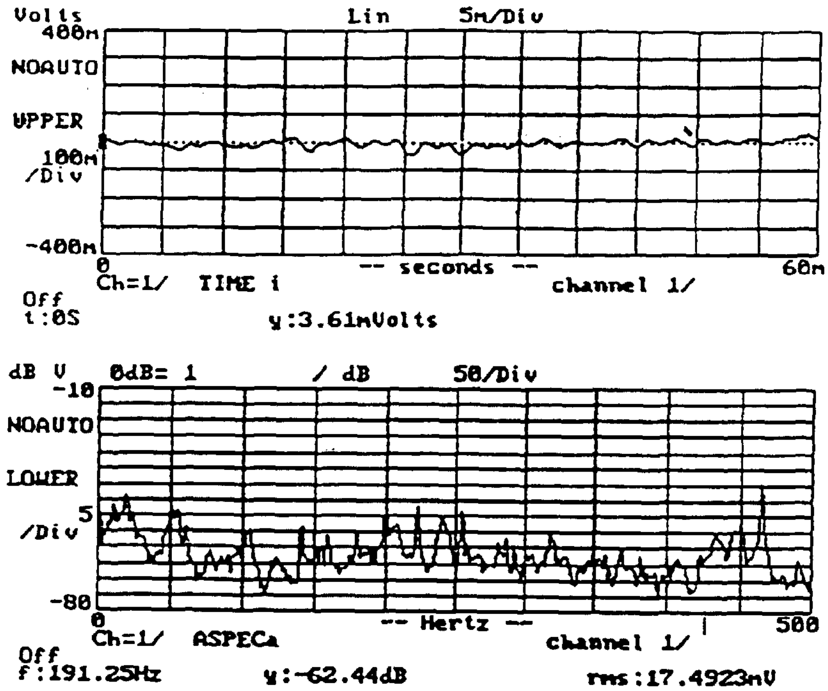

Control off
Control on
θ
0°
45°
-45°
90°
-90°
91
90
100
75
50
25
0
25
50
75
100
Radiated Sound Pressure Level (dB)

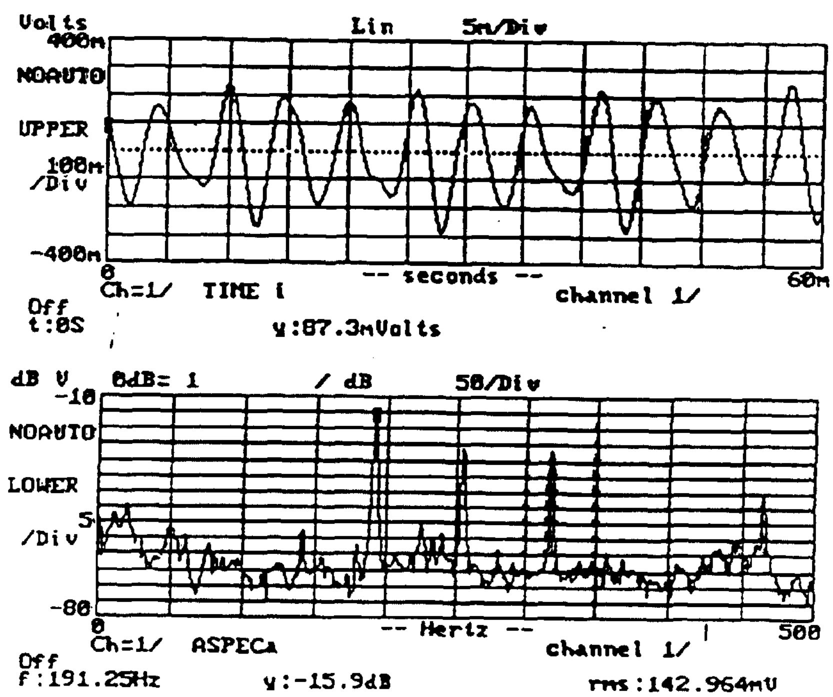
FIG 5

NCT ACTIVE ENCLOSURE - TEST RESULTS



Control On

FIG 6



Control Off