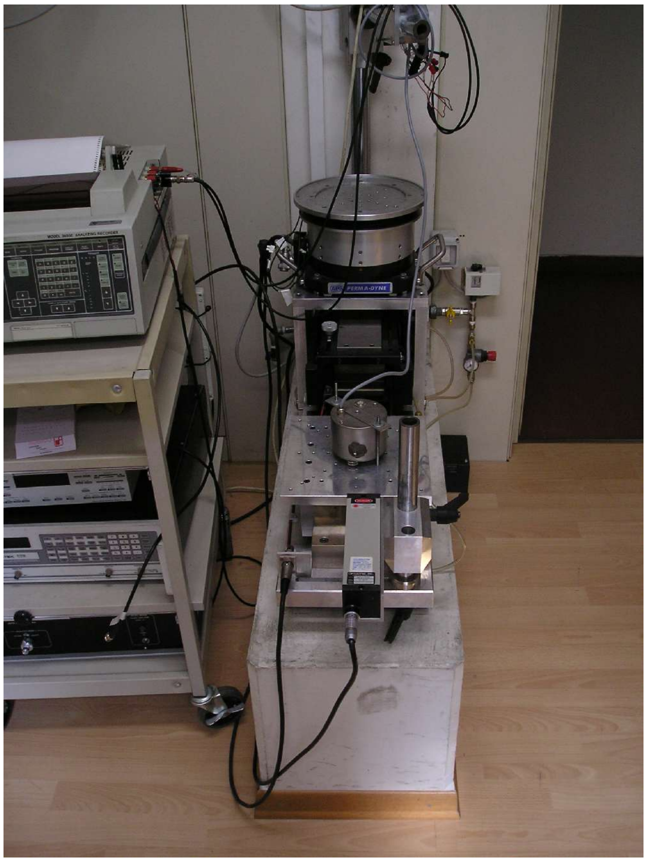
Istituto Nazionale di Oceanografia e di Geofisica Sperimentale
Centro di Ricerche Sismologiche di Udine

Relazione tecnica relativa al metodo diretto di calibrazione di sensori sismometrici tramite tavola vibrante.



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Il Direttore del Dipartimento CRS: Dr. E. Priolo

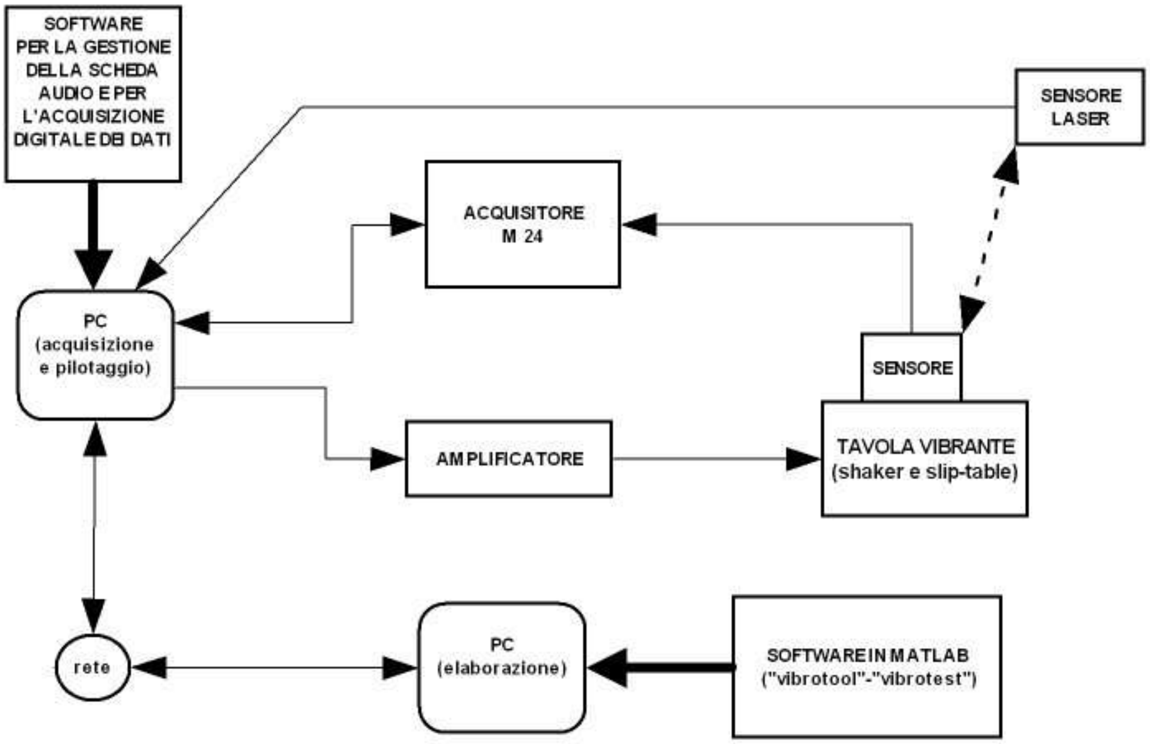
Enrico Priolo

Rel. OGS-11/2005/CRS-3
20 Luglio, 2005

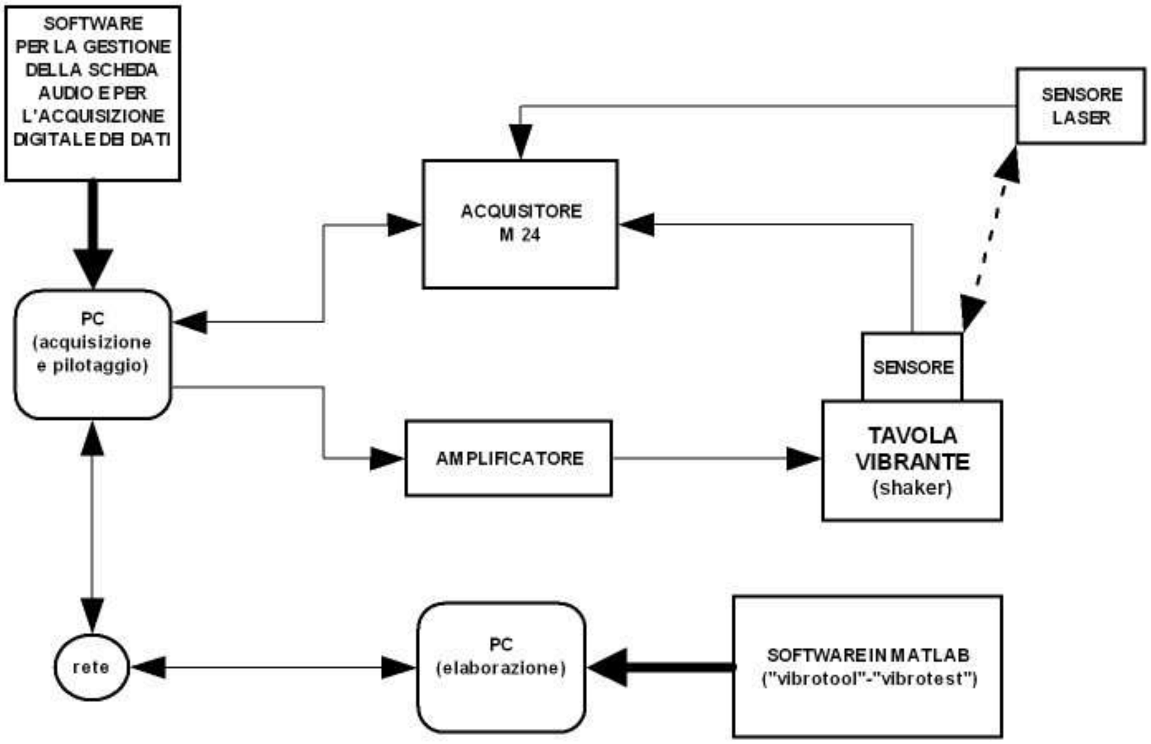
Oggetto: si descrive il metodo messo a punto presso il Dipartimento C.R.S. di Udine per la calibrazione diretta dei sensori sismometrici sia in verticale che in orizzontale tramite tavola vibrante e sensori campioni di spostamento a raggio laser.

SCHEMI A BLOCCHI PER LA CALIBRAZIONE CON IL METODO DIRETTO

a) Calibrazione delle due componenti orizzontali



b) Calibrazione della componente verticale



Spiegazione degli schemi a blocchi

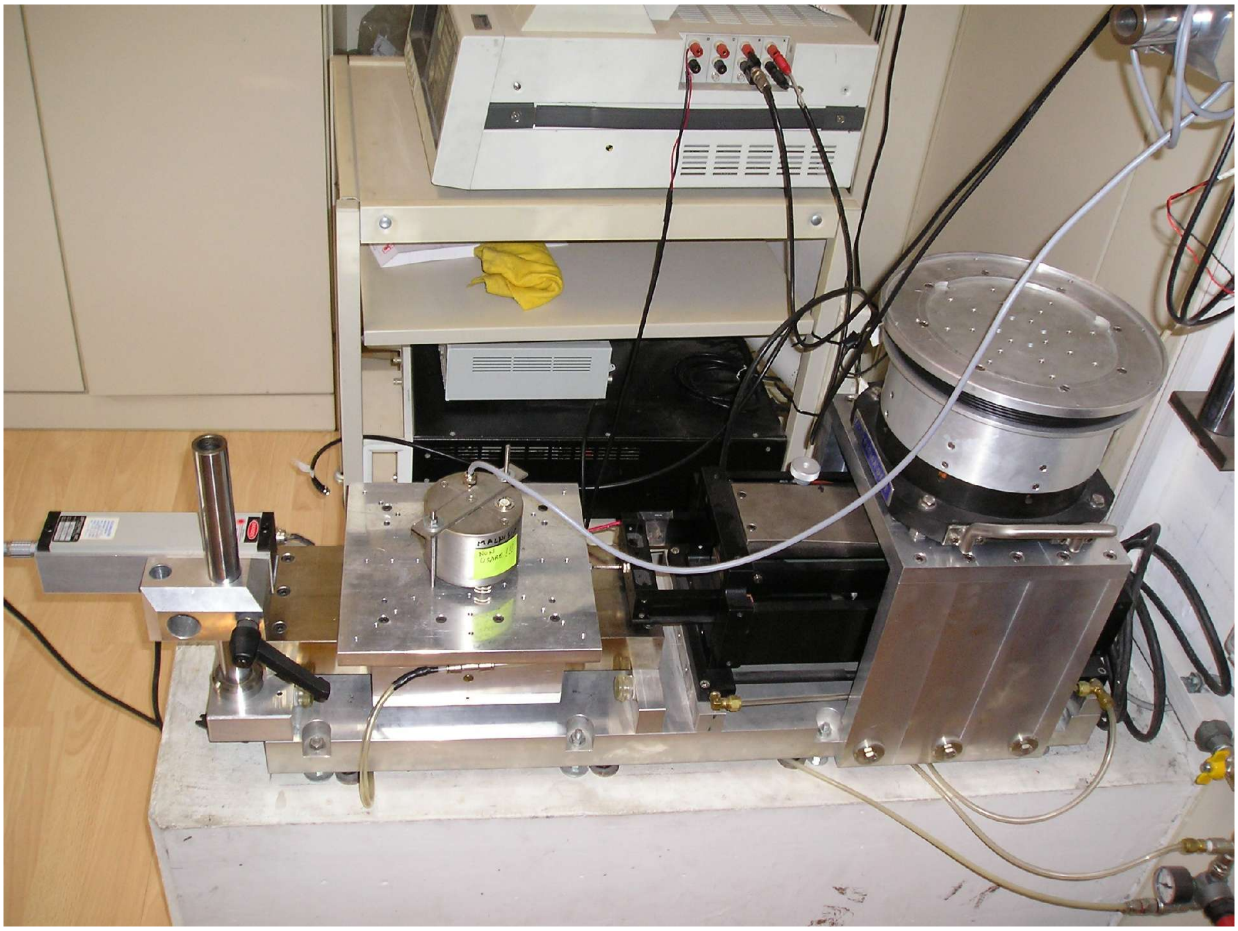


Figura 1 “Rappresentazione della tavola vibrante”

Shaker elettrodinamico verticale: E’ stato utilizzato uno shaker con caratteristiche tali da permettere l’utilizzo di sensori fino a 11 Kg di peso su una superficie di appoggio di almeno 22 cm e range di frequenze tra 0 e 1 kHz. Il circuito magnetico, costituito da un magnete permanente e da materiale ferromagnetico speciale crea un forte flusso nel traferro nel quale è inserita una bobina avvolta attorno a un supporto cilindrico fissato a due membrane di gomma che permettono il corretto movimento della bobina in verticale senza attriti con le pareti. Le due membrane sono collegate alla parte fissa dello shaker mentre la bobina è fissata alla piastra di ancoraggio del sensore. La forza massima ottenibile è pari a 310 N.

Shaker elettrodinamico orizzontale: E’ stato utilizzato uno shaker con principio di funzionamento analogo a quello verticale ma con un sistema di sospensione pneumatica della parte mobile che consente di eliminare gli attriti e di ottenere corse lunghe fino a 120 mm. Le frequenze massime applicabili sono intorno ai 200 Hz. La forza massima che può sviluppare è di 133 N.

Tavola orizzontale (slip-table): Questa componente ha la funzione di sostenere il peso del sensore sotto test senza permettere che vi siano forze di attrito che frenerebbero il moto e potrebbero provocare abrasioni all’apparecchiatura durante il movimento orizzontale. Per evitare questo inconveniente è stato utilizzato un sistema di lubrificazione ad aria compressa.

<u>Acquisitore M 24</u>: Si presenta come un acquisitore a tre canali che serve per amplificare e convertire da analogico a digitale il segnale proveniente dal sensore da calibrare; è interfacciato con il pc che pilota la tavola tramite un collegamento seriale. La dinamica del convertitore è pari a 24 bit e la velocità di campionamento è di 500 campioni al secondo.

Figura 2: "Acquisitore M 24"

<u>PC per l'acquisizione ed il pilotaggio del segnale</u>: è un pc impostato su sistema operativo Linux che contiene al suo interno dei software le cui funzioni principali sono la gestione ed il controllo della scheda audio e l'acquisizione digitale dei dati. Questo pc è collegato in rete e quindi può comunicare con il pc per l'elaborazione del segnale.

Figura 3: "Computer di acquisizione"

Scheda di interfaccia tra il sensore e il pc: è basata su un'architettura a microprocessore ed utilizza un chip di logica programmabile (128 macrocelle) ed un convertitore A/D veloce (660 ns) per tradurre in formato numerico i segnali provenienti dal sensore laser interferometrico. Utilizza inoltre una memoria statica da 512 Kbyte (FIFO) come buffer transitorio.

Figura 4"Scheda di interfaccia"

Scheda audio "Sigma – Delta Crystal CS4231": consiste in una normale scheda audio sound blaster che è stata modificata all'uscita attraverso l'eliminazione del filtro passa – alto in output. Questa operazione ha consentito di allargare ulteriormente la banda di frequenza dai 20 Hz iniziali a 0 Hz. La sua funzione principale è quella di far uscire il segnale che dopo essere stato amplificato andrà a pilotare la tavola.

Figura 5a: "Scheda audio modificata"

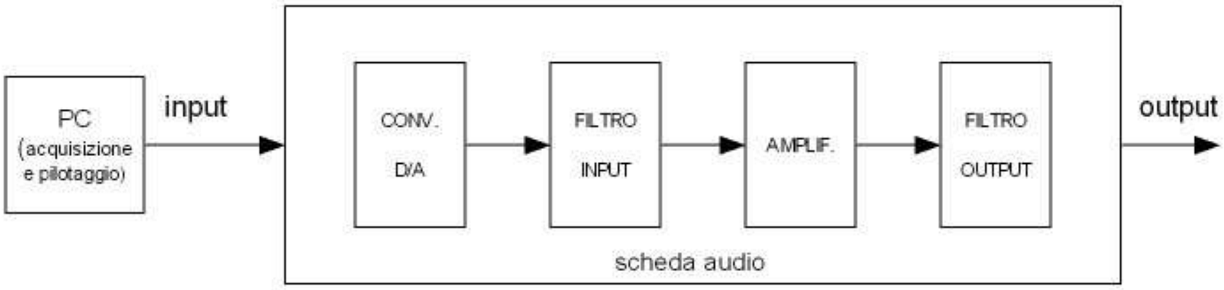


Figura 5b: "Rappresentazione della struttura della scheda audio Sigma – Delta Crystal CS4231"

<u>Sensori laser</u>: sono stati utilizzati due sensori diversi per ciascuna delle due tarature. Precisamente per la calibrazione delle due componenti orizzontali abbiamo utilizzato il sensore laser LDS-3000 che è un sensore laser che sfrutta il principio della riflessione-interferenza delle onde luminose.
Questi è un sensore di spostamento che permette di effettuare misure in un range di 400 mm con una risoluzione di ± 2.54 nanometri.
Per la calibrazione della componente verticale, invece, abbiamo utilizzato il sensore LM 300 che sfrutta il principio della diffusione delle onde luminose.
Quest'ultimo è un sensore di spostamento che permette di effettuare misure in un range di ± 3 mm con una risoluzione di 200 nanometri in una banda di frequenze che va da 0 Hz a 400 Hz.
<u>N.B</u>. I due sensori laser sono intercambiabili nelle due tipologie di calibrazione quindi non è obbligatorio utilizzare tassativamente il primo nella calibrazione in orizzontale ed il secondo in quella in verticale.

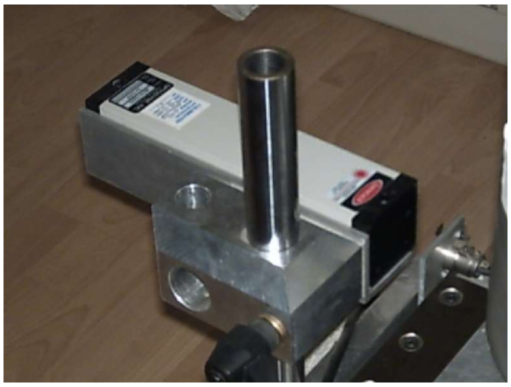


Figura 6a: "Sensore laser interferometrico"

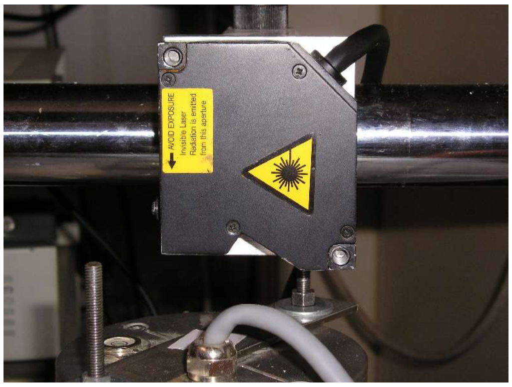


Figura 6b: "Sensore laser a diffusione"

Amplificatore: è stato utilizzato un amplificatore di potenza (modello 124) che consente di erogare al massimo 250 VA r.m.s. di potenza per alimentare la tavola. Esso consente di utilizzare una forza massima pari a 310 Newton.

Figura 7: "Amplificatore di potenza"

PC per l'elaborazione del segnale di pilotaggio: è un pc provvisto di un software realizzato con "Matlab" attraverso il quale è possibile generare ed eventualmente modificare il segnale che andrà a pilotare la tavola vibrante. Questo pc è collegato in rete e quindi può comunicare con il pc per l'acquisizione e il pilotaggio del segnale.

Segnale per il pilotaggio della tavola vibrante: all'inizio per pilotare la tavola vibrante si pensò di utilizzare un segnale che si avvicinasse il più possibile ad un impulso ideale.
A tal fine, conoscendo l'impossibilità di riprodurre un impulso ideale nella pratica, si utilizzò un impulso rettangolare con un periodo T molto stretto (e quindi con elevato contenuto armonico).
Ci si accorse però che questo tipo di segnale non dava gli effetti desiderati in quanto c'era il rischio di mandare in saturazione l'apparecchiatura e quindi di mettere a repentaglio la linearità del sistema.
Le alternative potevano essere:

- creare un segnale modulato in frequenza (cioè uno "sweep")
- realizzare un segnale con il metodo delle armoniche separate (o discrete), metodo che permette di ottenere un segnale che è il risultato della somma di un certo numero di armoniche scelte a determinati valori di frequenza
- utilizzare un rumore gaussiano

Si è scelta l'ultima soluzione tenendo conto delle seguenti precisazioni.

Visto che la tavola si comporta come un filtro che taglia determinate frequenze, il rumore gaussiano necessita di un'equalizzazione in grado di recuperare le armoniche che sono state attenuate dalla tavola stessa.

Per questo motivo si è corretta la risposta della tavola tramite filtraggio di equalizzazione. In questo modo è possibile ottenere un segnale a velocità costante alle varie frequenze.

Inoltre il segnale è stato smussato con la tecnica del tapering e ricampionato con una frequenza di campionamento pari a 1 kHz in quanto la scheda audio esigeva una frequenza di campionamento minima di 1 kHz.

Tutta l'elaborazione dei segnali di pilotaggio della tavola è stata effettuata mediante l'utilizzo del software "Matlab".

Come effettuare una calibrazione

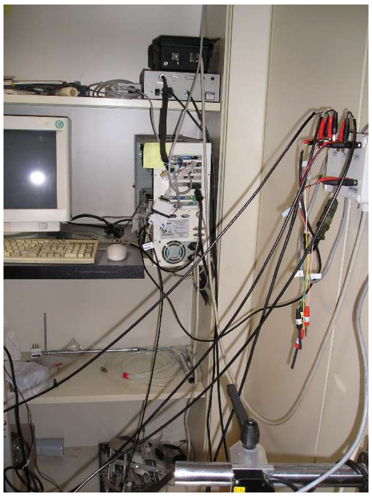
Operazioni preliminari alla calibrazione in orizzontale del sensore

Per prima cosa si blocca con apposita staffa il sensore sulla tavola forata la quale permette di poter utilizzare sensori di varie dimensioni; si consiglia di posizionare il sensore il più possibile al centro della tavola controllando che quest'ultimo sia a bolla.
Successivamente si ruota il sensore sulla tavola forata in modo che le due componenti orizzontali siano inclinate di un angolo di 45° rispetto al moto della tavola.
A questo punto si applica sul sensore il prisma riflettore, un prisma di vetro studiato per riflettere il raggio incidente proveniente dal sensore laser nella stessa direzione di provenienza.
Dopo aver fissato il prisma al sensore con del pongo si deve controllare il ritorno del raggio al sensore laser.
In seguito si andranno a preparare le connessioni in modo che queste non creino interferenze meccaniche con la parte mobile della tavola (il cavo uscente dal sensore deve essere tenuto lasco).
Nel caso si dovessero invertire le polarità delle due componenti orizzontali del sensore non si verrà ad avere alcun danno ma si tenga presente che sull'oscilloscopio le fasi saranno aumentate di 180°.
Tanto per fissare le idee per quanto concerne le connessioni si vedano i collegamenti dei piedini del connettore femmina LE-3Dlite (allegato n°1).

Calibrazione delle due componenti orizzontali del sensore

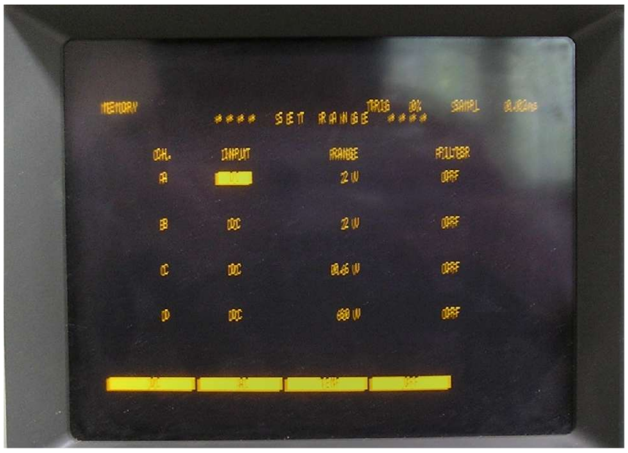
Per effettuare una calibrazione corretta si eseguano i punti che seguono:

1) Verificare che tutti i collegamenti siano stati fatti correttamente



2) Controllare che non sia attivo il bypass del pressostato (switch posizionato sopra il pressostato)

3) Impostare sull'oscilloscopio le scale delle tensioni e dei tempi e selezionare l'opzione che permette di visualizzare il display duale


MEMORY TRIG 0% SAMPL 0.02ms
**** SET RANGE ****

CH.	INPUT	RANGE	FILTER
A	[illegible]	2 V	OFF
B	DC	2 V	OFF
C	DC	0.6 V	OFF
D	DC	60 V	OFF


MEMORY TRIG 0% SAMPL 0.02ms
**** SET DISPLAY FORMAT ****

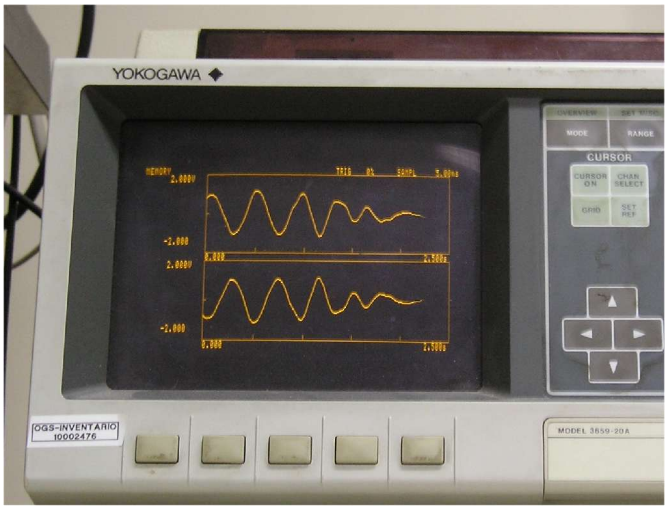
DISPLAY MODE = [illegible]

UPPER 1 = V1
2 = V2

LOWER 1 = V3
2 = OFF

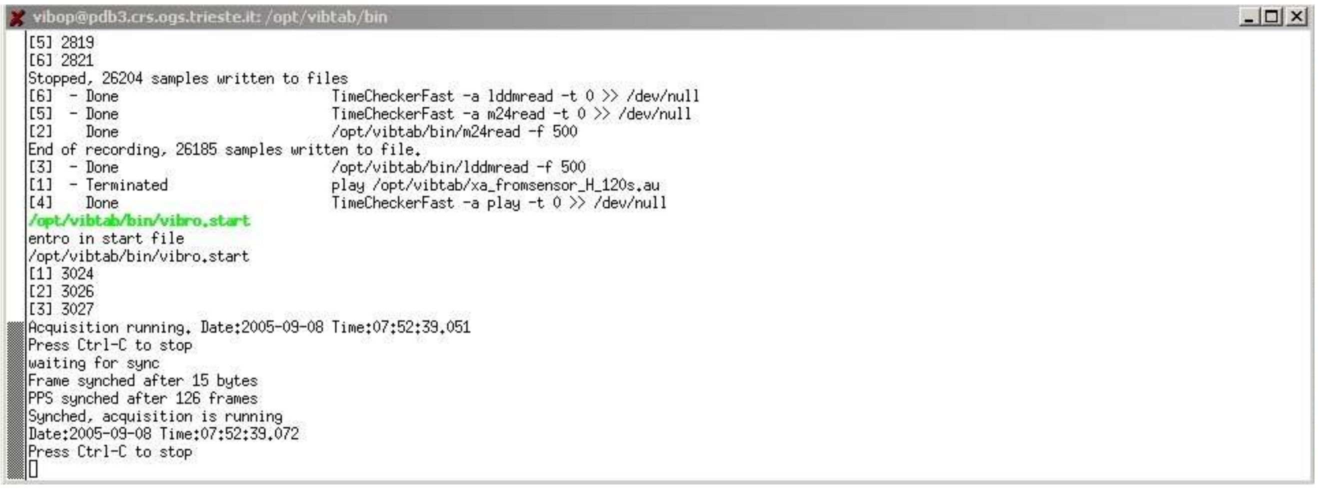
4) Osservare sull'oscilloscopio i due segnali provenienti dalle due componenti orizzontali del sensore

5) Verificare che i due segnali siano uguali fra di loro per avere la conferma che tutte le operazioni precedenti siano state effettuate correttamente



6) Accendere il pc con i software di acquisizione e di pilotaggio e quindi l’acquisitore che è collegato al pc

7) Avviare il software di acquisizione di cui al punto 6 (script linux)
8) Accedere come “super user” digitando “su”
9) Entrare nella directory “cd/opt/vibtab/bin”
10) Lanciare il programma “./dmvibro”



```
[5] 2819
[6] 2821
Stopped, 26204 samples written to files
[6]  - Done                    TimeCheckerFast -a lddmread -t 0 >> /dev/null
[5]  - Done                    TimeCheckerFast -a m24read -t 0 >> /dev/null
[2]    Done                    /opt/vibtab/bin/m24read -f 500
End of recording, 26185 samples written to file.
[3]  - Done                    /opt/vibtab/bin/lddmread -f 500
[1]  - Terminated              play /opt/vibtab/xa_fromsensor_H_120s.au
[4]    Done                    TimeCheckerFast -a play -t 0 >> /dev/null
/opt/vibtab/bin/vibro.start
entro in start file
/opt/vibtab/bin/vibro.start
[1] 3024
[2] 3026
[3] 3027
Acquisition running. Date:2005-09-08 Time:07:52:39.051
Press Ctrl-C to stop
waiting for sync
Frame synched after 15 bytes
PPS synched after 126 frames
Synched, acquisition is running
Date:2005-09-08 Time:07:52:39.072
Press Ctrl-C to stop
```

11) Accendere il sensore laser e lasciarlo acceso per circa mezzora in modo che possa raggiungere la sua temperatura di funzionamento

12) Sull’oscilloscopio reimpostare il display duale per visualizzare tutte e due le tracce

13) Settare il commutatore voltage-current sulla posizione *off* e il potenziometro multigiri sul valore prestabilito e poi accendere l'amplificatore

14) A questo punto aprire l'aria per alimentare la tavola controllando che la pressione raggiunga valori prossimi alle 2-2.5 Atm tramite il pressostato (strumento che regola automaticamente i valori di pressione e che è posto a monte del rubinetto)

15) Settare il commutatore voltage-current sulla posizione "voltage"

16) Lanciare da pc il programma “Matlab” (una volta lanciato il Matlab è presente il prompt dei comandi)

Current Directory: C:\Programmi\MATL

```
ans =

/opt/vibtab/xa_fromsensor_H_120s.au

>>
```

17) Avviare la scheda audio che genera il rumore bianco tramite la procedura chiamata “vibrotool”; dopo alcuni secondi apparirà una schermata che richiede la durata in secondi del test ed il tipo di rumore equalizzato da utilizzare.

Span 120 s

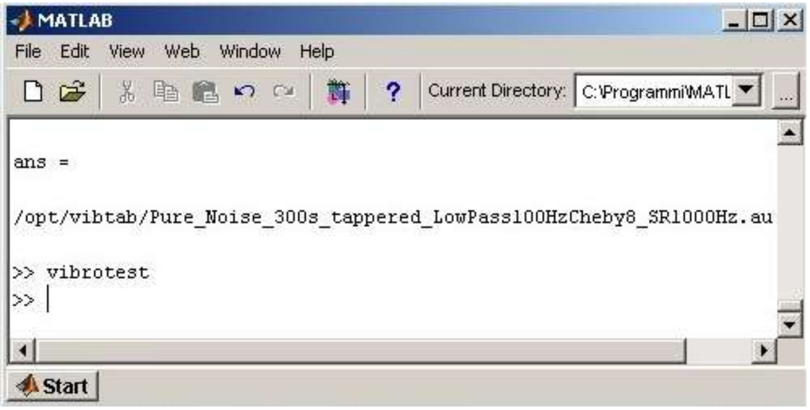
/opt/vibtab/xa_fromsensor_H_120s.au

18) Dopo aver digitato il numero di secondi, che dipenderà dal tipo di sensore in esame, far partire il test

Please wait...

19) Verificare che l’acquisizione sul pc di cui al punto 6 sia avviata

20) Una volta terminato il test, lanciare la procedura “vibrotest” in Matlab che fornirà le risposte in frequenza di modulo e fase del sensore sotto test

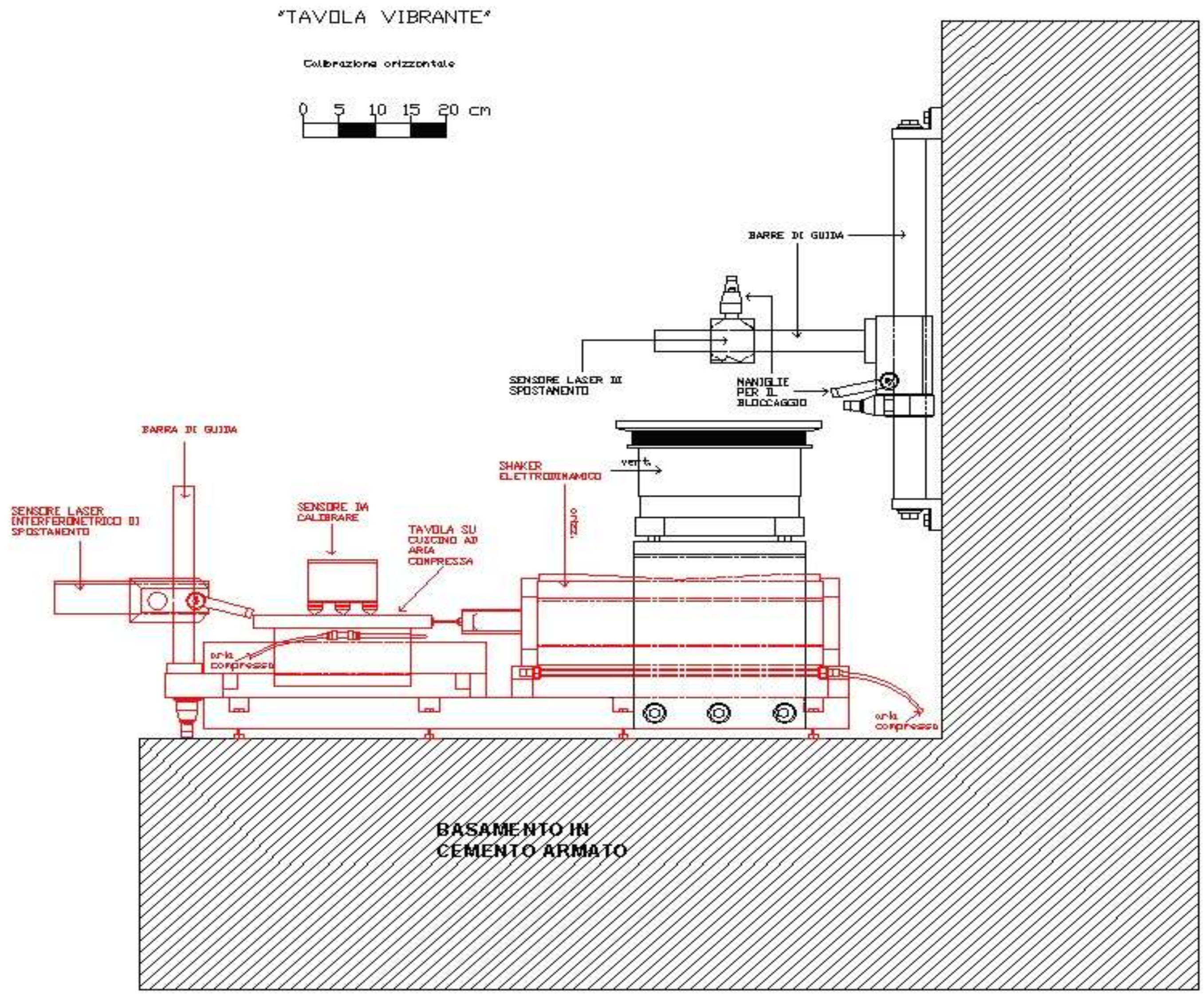


Current Directory: C:\Programmi\MATL

```
ans =

/opt/vibtab/Pure_Noise_300s_tappered_LowPass100HzCheby8_SR1000Hz.au

>> vibrotest
>> |
```


"TAVOLA VIBRANTE"
Calibrazione orizzontale
0 5 10 15 20 cm
BARRE DI GUIDA
SENSORE LASER DI SPOSTAMENTO
MANIGLIE PER IL BLOCCAGGIO
BARRA DI GUIDA
SENSORE LASER INTERFEROMETRICO DI SPOSTAMENTO
SENSORE DA CALIBRARE
TAVOLA SU CUSCINO AD ARIA COMPRESSA
SHAKER ELETTRODINAMICO
vert.
orizz.
aria compressa
aria compressa
BASAMENTO IN CEMENTO ARMATO

Operazioni preliminari alla calibrazione in verticale del sensore

La prima operazione da effettuare è prendere il sensore da calibrare e bloccarlo con una staffa sullo shaker. Quest'ultimo è uno strumento che compie dei movimenti oscillatori verticali e che sfrutta lo stesso principio di funzionamento di un altoparlante.

Si consiglia di posizionare il sensore il più possibile al centro dello shaker controllando che sia a bolla.

A questo punto si dovrà applicare sul sensore da calibrare un pezzo di nastro adesivo bianco che presenti una superficie non riflettente in modo da consentire il corretto funzionamento del sensore laser che si basa non sul principio di riflessione (come quello utilizzato per la calibrazione delle due componenti orizzontali) ma bensì sul principio della diffusione della luce.

Successivamente si andrà a posizionare il sensore laser in modo che la distanza tra quest'ultimo e il sensore da calibrare sia il più possibile vicina a 30 mm.

Alla distanza di 30 mm corrisponderà sul display digitale, collegato al sensore laser, una lettura 0.000 con una tolleranza di ± 0.2 mm.

In seguito si procederà, come per la calibrazione orizzontale, andando a preparare le connessioni e facendo attenzione che queste non creino interferenze meccaniche con la parte mobile della tavola.

Tanto per fissare le idee per quanto concerne le connessioni si vedano i collegamenti dei piedini del connettore femmina LE-3Dlite (allegato n°1).

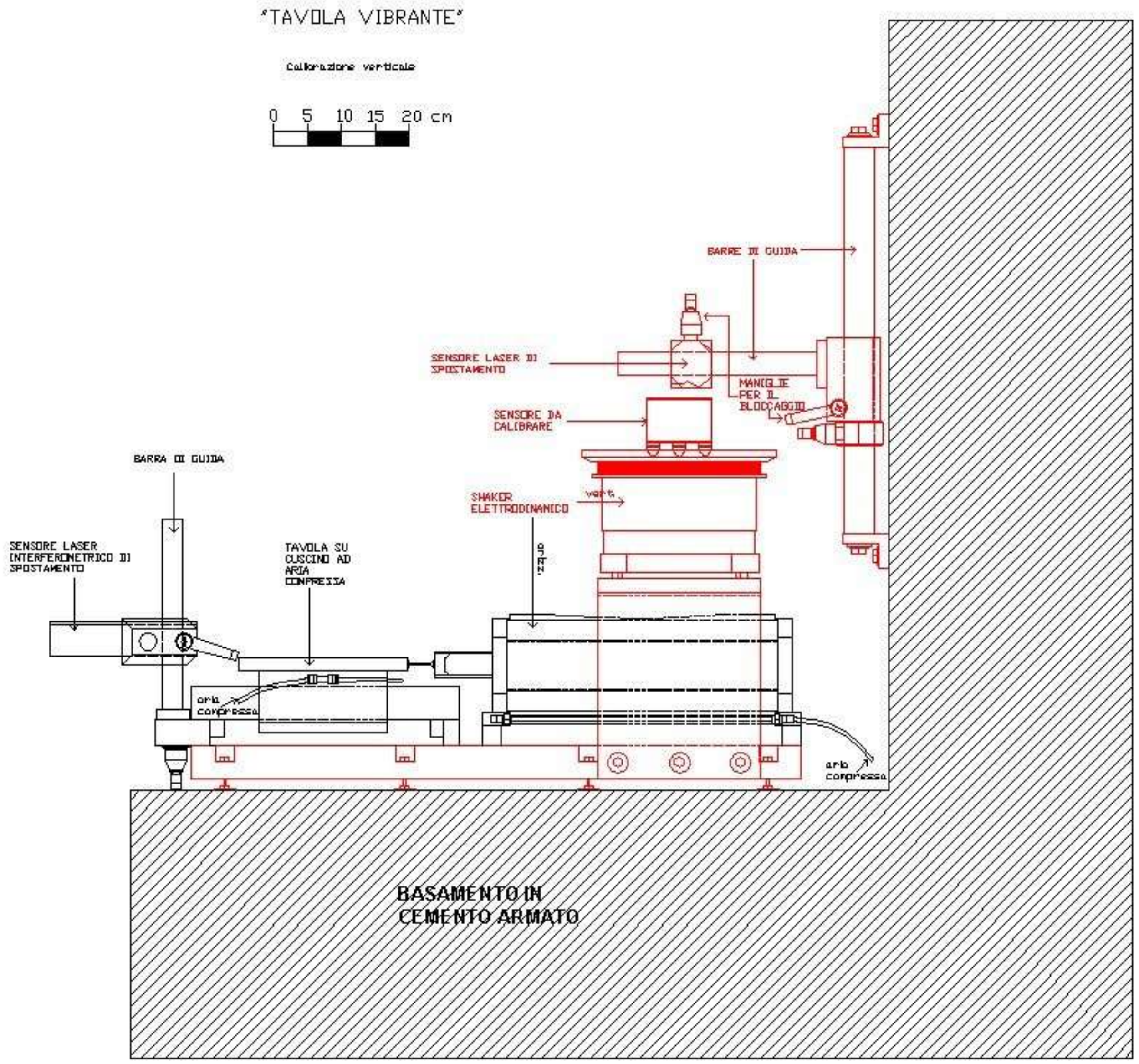
Calibrazione della componente verticale del sensore

La calibrazione in verticale del sensore è molto simile a quella in orizzontale tranne alcuni particolari.

Innanzitutto il sensore da calibrare verrà posizionato sulla tavola forata dello shaker elettrodinamico verticale; secondariamente il segnale utilizzato per pilotare la tavola vibrante sarà diverso da quello usato nella calibrazione orizzontale in quanto diverse sono le masse in gioco e le forze antagoniste dovute alle sospensioni elastiche utilizzate per contrastare la forza di gravità.

Infine il bypass del pressostato dovrà essere attivo mentre il compressore dovrà essere spento.

Pertanto, per effettuare una calibrazione in verticale si eseguano pure i punti elencati nella procedura di calibrazione delle componenti orizzontali, ma si tenga conto dei particolari appena esposti.


"TAVOLA VIBRANTE"
Calibrazione verticale
0 5 10 15 20 cm
BARRE DI GUIDA
SENSORE LASER DI SPOSTAMENTO
MANIGLIE PER IL BLOCCAGGIO
SENSORE DA CALIBRARE
SHAKER ELETTRODINAMICO
vert.
orizz.
BARRA DI GUIDA
SENSORE LASER INTERFEROMETRICO DI SPOSTAMENTO
TAVOLA SU CUSCINO AD ARIA COMPRESSA
aria compressa
aria compressa
BASAMENTO IN CEMENTO ARMATO

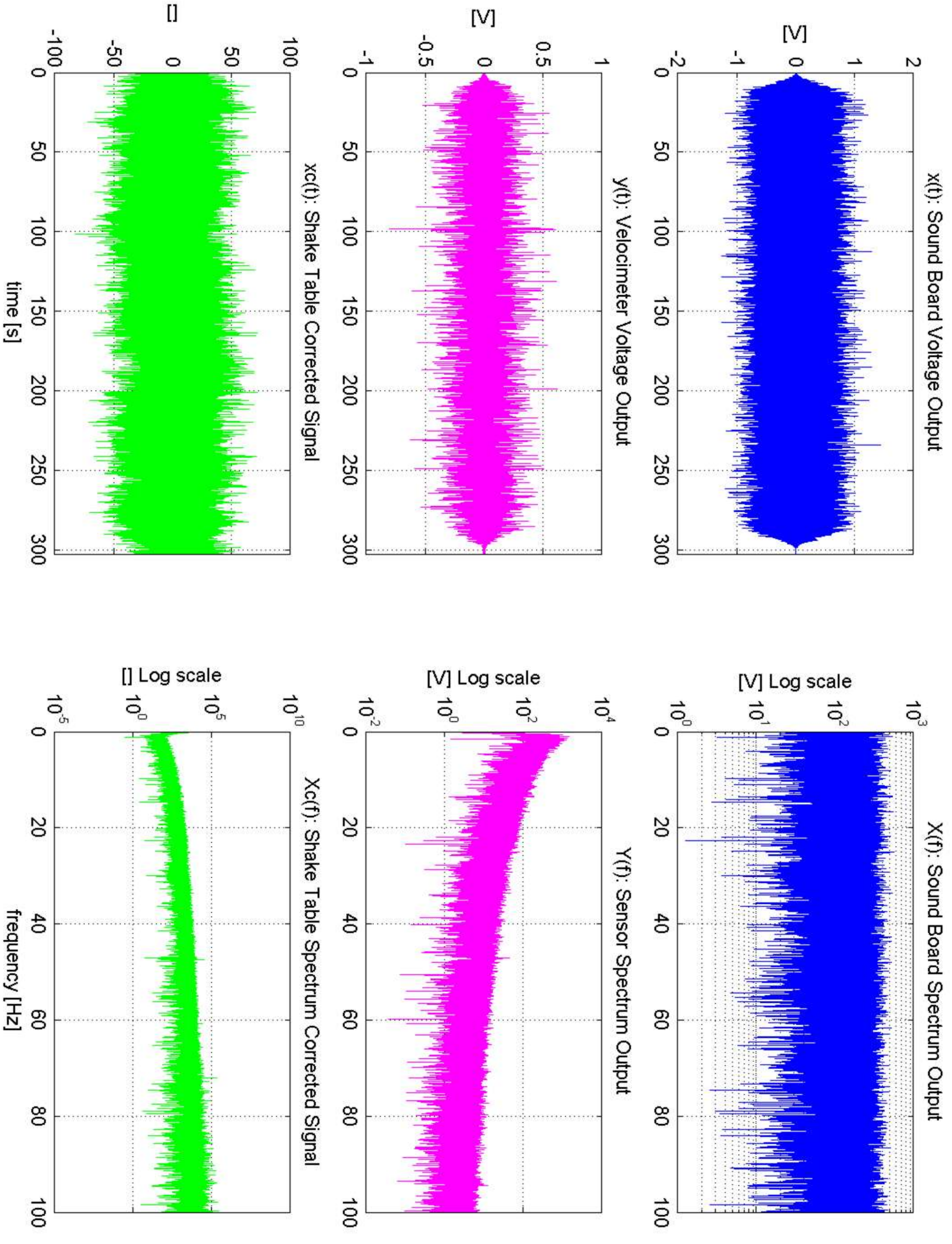


Figura 8: "Risposte nel tempo e in frequenza di alcuni segnali;in blu è rappresentato il rumore bianco originario, in fuxia è rappresentato il segnale all'uscita del sensore mentre in verde è rappresentato il segnale di pilotaggio equalizzato ma privo di filtraggio"

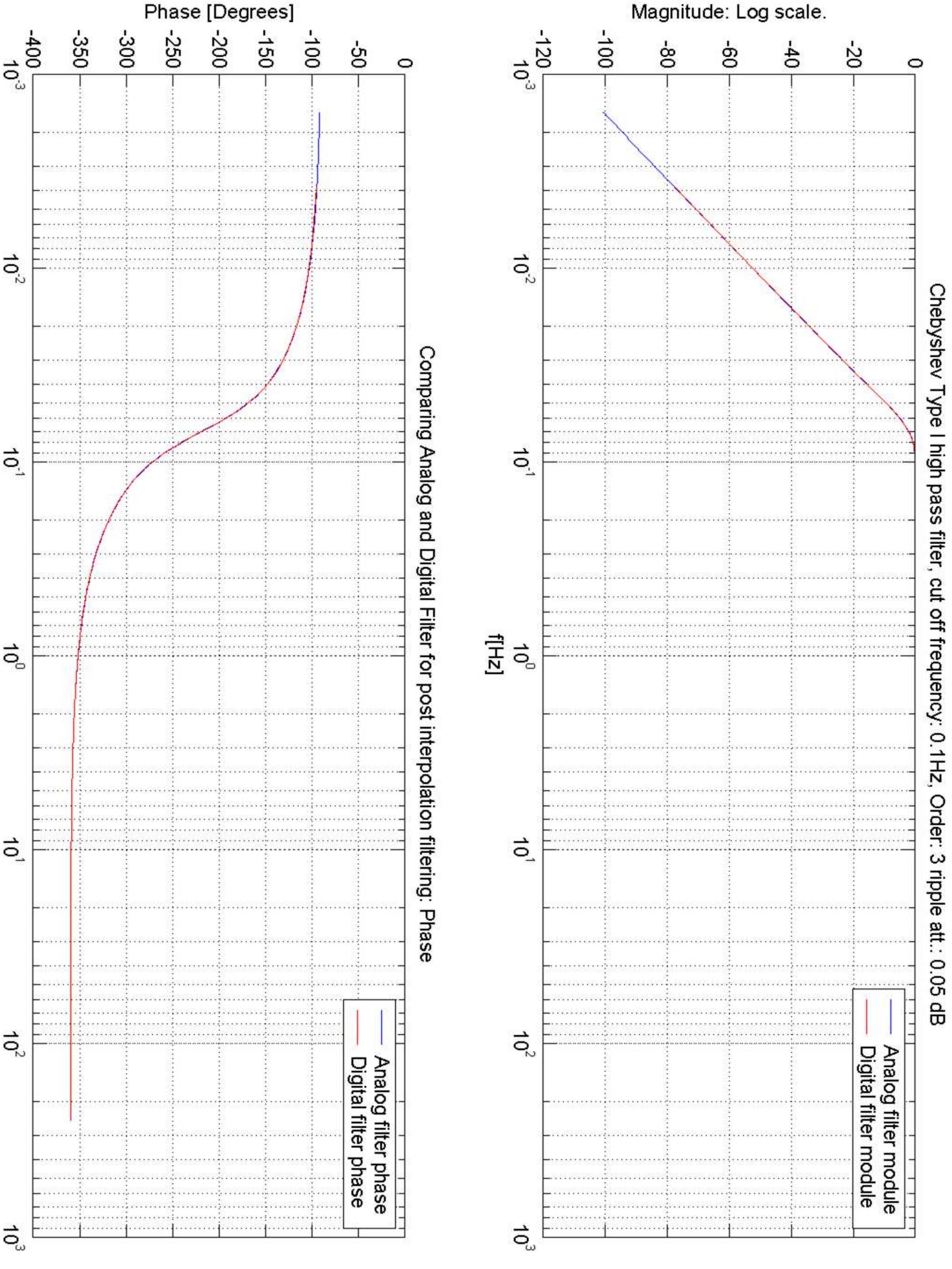


Figura 9:"Rappresentazione in frequenza di modulo e fase del filtro passa – alto utilizzato per eliminare i valori di frequenza molto bassi presenti nel segnale di pilotaggio della tavola vibrante "

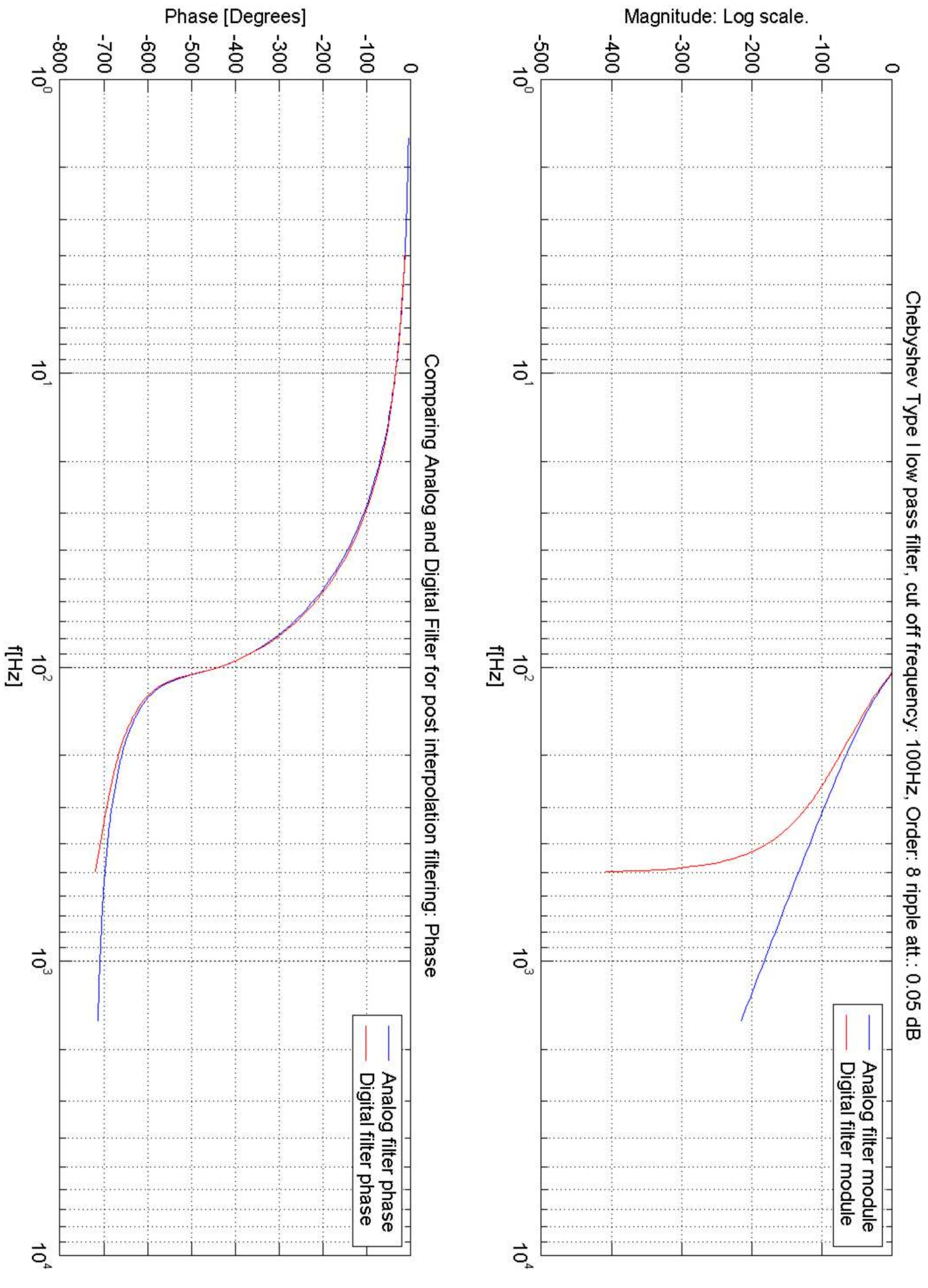


Figura10:"Rappresentazione in frequenza di modulo e fase del filtro passa – basso utilizzato per eliminare le alte frequenze presenti nel segnale di pilotaggio della tavola vibrante "

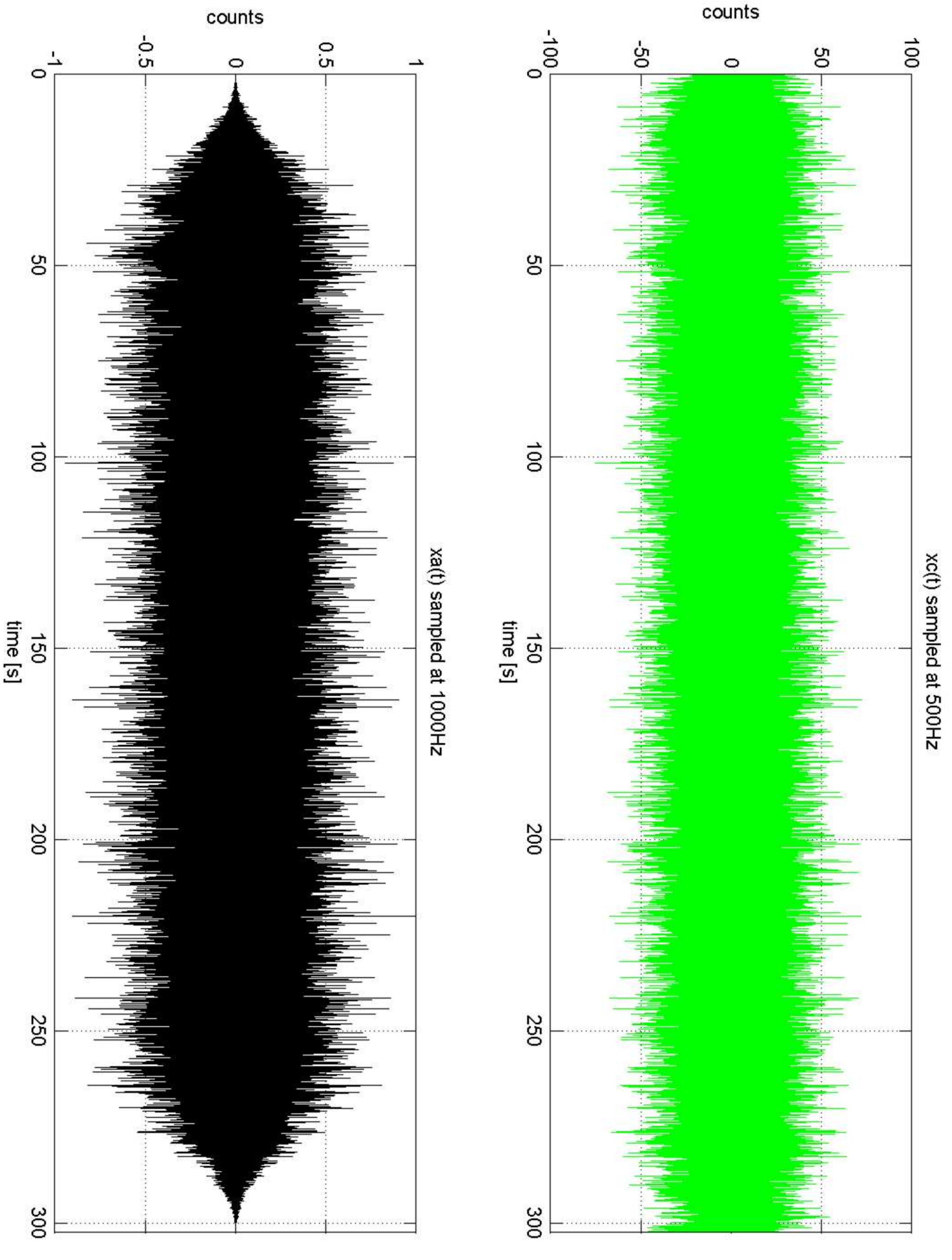


Figura 11:"Rappresentazione nel dominio del tempo del segnale di pilotaggio; in verde è rappresentato lo stesso segnale di figura 8 campionato con una frequenza di 500 Hz e filtrato mentre in nero è rappresentato il segnale di pilotaggio vero e proprio; quest'ultimo è stato ricampionato ad una frequenza di 1kHz e smussato alle estremità con la tecnica del tapering"

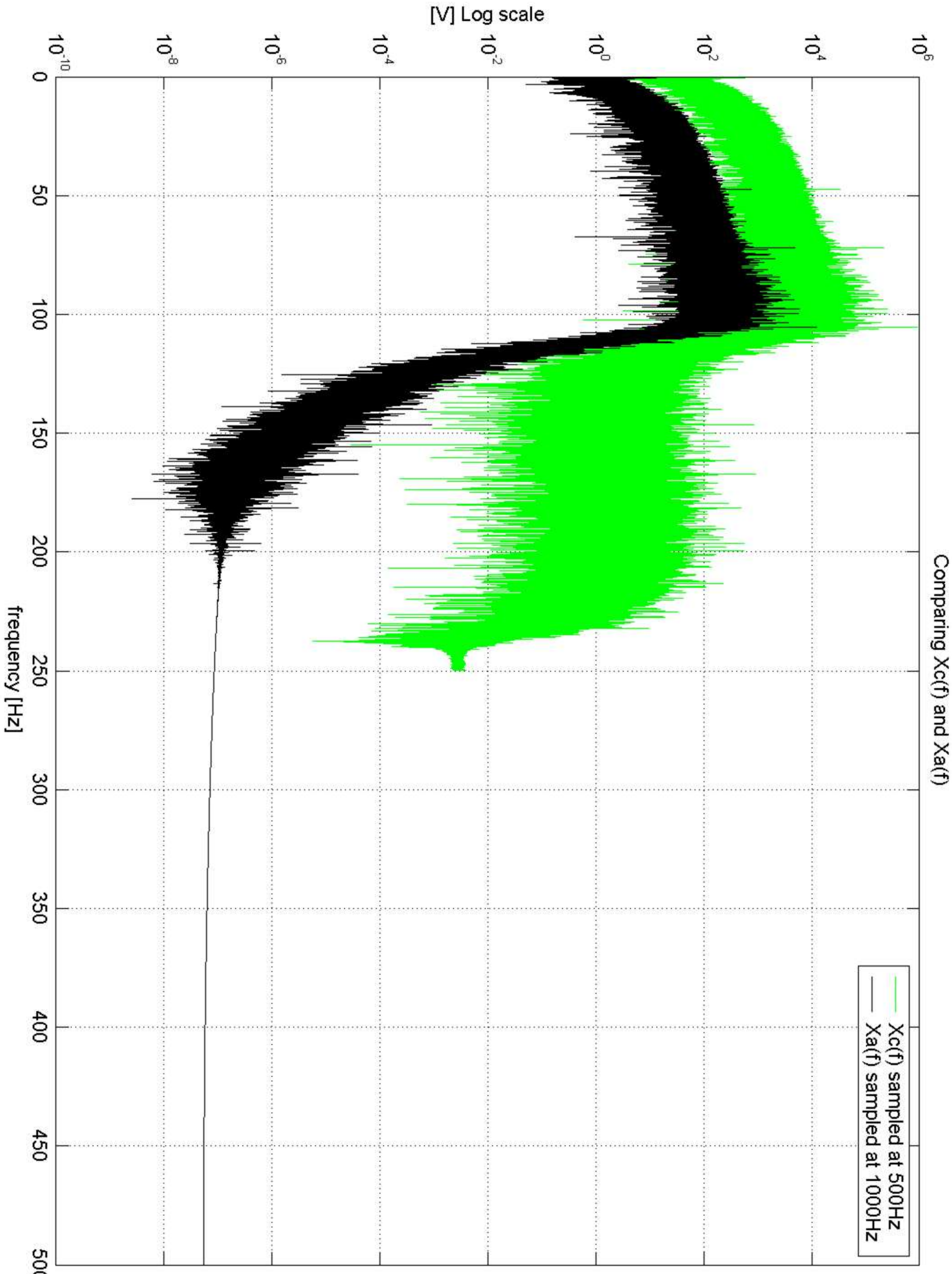


Figura 12:"Rappresentazione in frequenza del modulo dei segnali di figura11"

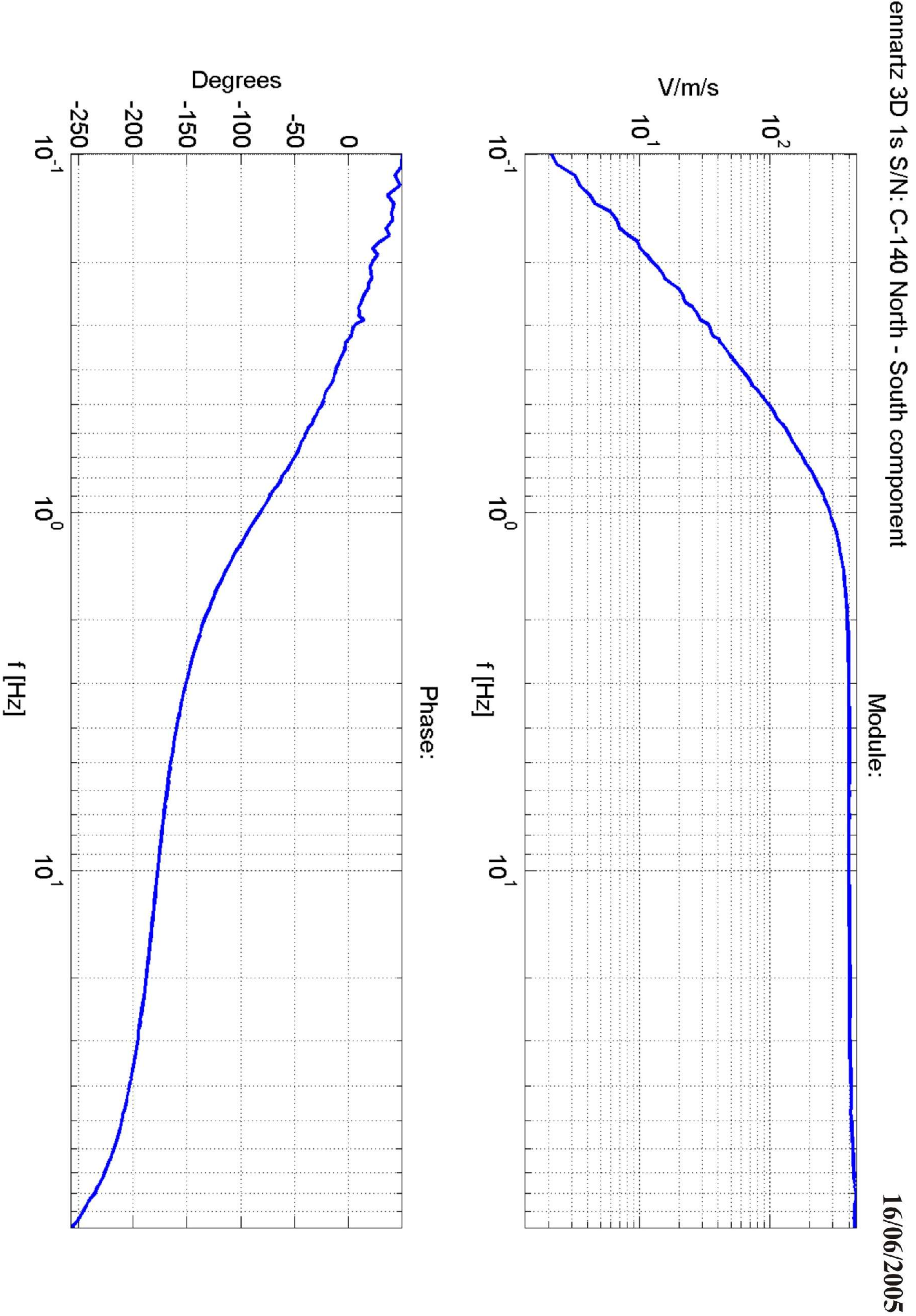


Figura 13: "Risposta in frequenza della prima componente orizzontale di un sensore Lennartz"

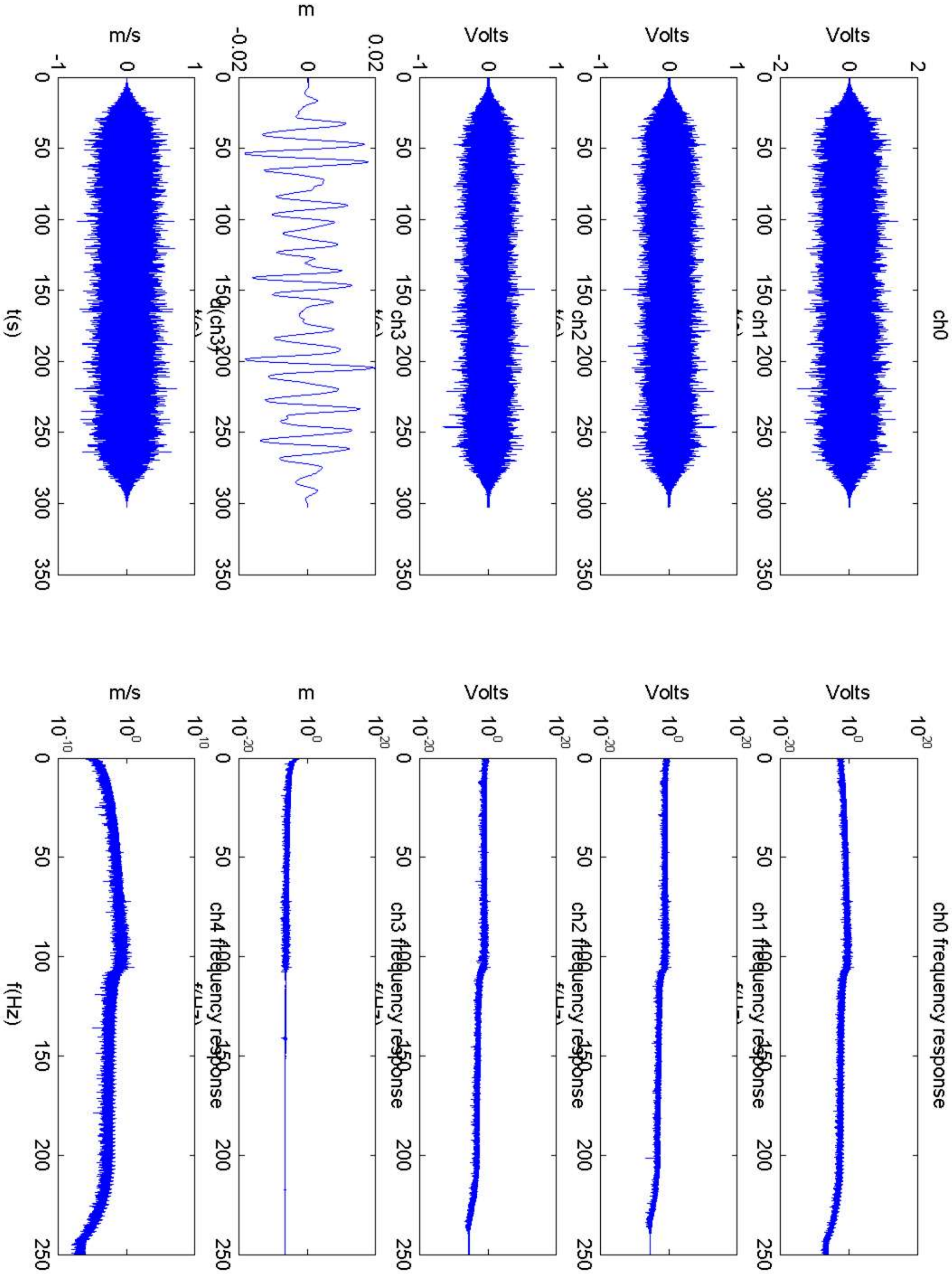


Figura 14: "Rappresentazione del segnale di pilotaggio della tavola e del segnale acquisito dal sensore"

frequency [Hz]	Module [V/(m/s)]	Phase [°]
0.00	NaN	NaN
0.10	2.11	49.86
0.20	12.56	21.84
0.30	33.82	5.53
0.40	60.74	-12.08
0.50	96.66	-24.68
0.60	136.87	-39.42
0.70	176.43	-50.49
0.80	218.64	-62.40
0.90	256.20	-73.21
1.00	285.34	-82.16
2.00	388.51	-134.13
3.00	397.64	-151.06
4.00	400.55	-159.57
5.00	400.34	-164.91
6.00	399.86	-168.50
7.00	399.93	-171.37
8.00	398.67	-173.65
9.00	399.55	-175.47
10.00	399.56	-177.06
15.00	403.33	-183.21
20.00	406.53	-187.87
25.00	406.29	-191.95
30.00	405.80	-195.77
35.00	410.48	-199.49
40.00	414.94	-203.13
45.00	415.30	-206.74
50.00	417.18	-210.41
55.00	423.34	-214.18
60.00	429.55	-218.10
65.00	432.47	-222.04
70.00	436.51	-226.57
75.00	444.15	-230.81
80.00	453.17	-235.55
85.00	447.49	-242.05
90.00	440.54	-246.59
95.00	440.02	-251.41
100.00	NaN	NaN

Figura 15: “Listato dei dati inerenti alla fig.13”

ALLEGATI

Listato degli allegati

All. n°1 – Schema del connettore femmina LE-3Dlite

All. n°2 – Caratteristiche generali relative all'amplificatore di potenza (modello 124)

All. n°3 – Caratteristiche tecniche del sensore laser analogico LM 300

All. n°4 – Caratteristiche tecniche del sensore laser intereferometrico LDS-3000

All. n°5 – Documentazione tecnica relativa all'oscilloscopio (Yokogawa model 3655 analyzing recorder)

All. n°6 – Caratteristiche generiche e datasheets dello shaker elettrodinamico orizzontale

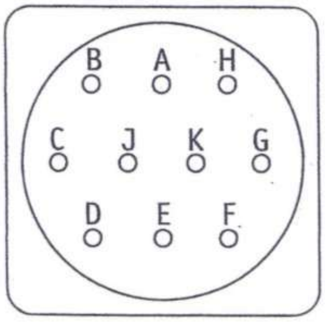
All. n°7 – Caratteristiche generiche e datasheets dello shaker elettrodinamico verticale

Connector pinout

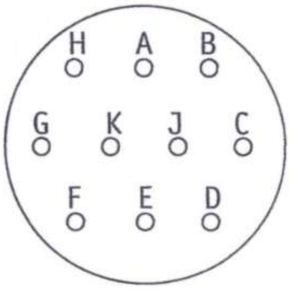
This chapter is for people needing to connect a Lennartz seismometer to some other (non-Lennartz) type of device or cable.

The **LE-3Dlite** and the **LE-1D** models have a short length of cable (approx. 1.5 to 2 meters) with a male connector permanently attached. If you need another type of connector you will have to cut off the factory-provided one and mount your own. The colors of the individual cables are given below. All other models have a female connector mounted on the geophone housing.

We will use Z, N, and E to designate the three orthogonal components. Z is the vertical component, N is "north" (see the chapter on "Leveling, orientation" for a definition).



female connector on
geophone housing
(LE-3D "classic",
LE-3D/5s, LE-3D/20s)



male connector on
geophone cable
(LE-3Dlite, LE-1D/V,
LE-1D/H)

Pin	Name	Remarks	Color
A	+Z	For LE-1D/H, this is the single horizontal component!	light brown
B	-Z	ditto	dark brown
C	+N	n/c for LE-1D/x	green
D	-N	ditto	yellow
E	+E	ditto	violet
F	-E	ditto	blue
G	+12V		orange
H	-CAL		pink
J	GND, SHLD	Signal ground and cable shield	black/white
K	0V	for 12 V supply	black

--- end of document ---

All. N°1

Model 124 Power Amplifier

All. N°2

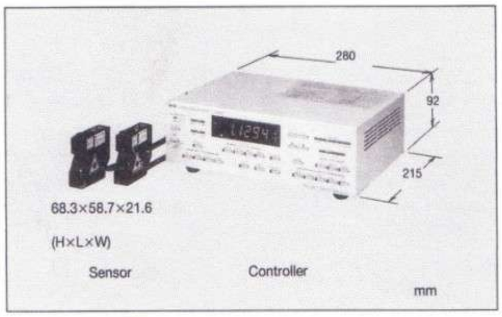
NAiS

Matsushita Automation Controls

MISURAZIONE LASER IN CLASSE 3B DI ELEVATA PRECISIONE PER UN'AMPIA GAMMA DI APPLICAZIONI

LM 300 Sensori Analogici Laser

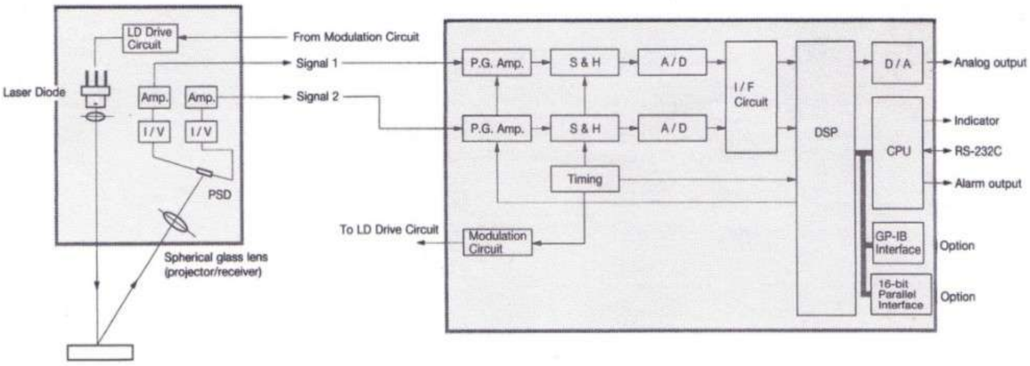
Elevata velocità di risposta 20 kHz e alta risoluzione 0,2 μm.



CARATTERISTICHE

- **Elevata velocità di risposta**
  L'elevata velocità di risposta di 20 kHz è ottenuta mediante una frequenza di campionamento pari a 50 kHz. Questa caratteristica rende la serie LM300 adatta a tutti quei processi dove è necessaria una misura molto precisa in tempo reale.
- **Misura molto accurata**
  L'uso di lenti sferiche in vetro ha fortemente limitato tutte le aberrazioni ottiche assicurando nello stesso tempo una rilevazione accurata anche in presenza di drastici cambiamenti di colore e materiale testato. Queste caratteristiche per esempio permettono una rilevazione precisa anche su gomma nera opaca.
- **Alta risoluzione**
  0,2 μm di risoluzione fanno della serie LM300 un dispositivo adatto a misurazioni di estrema precisione.
- **Versione a due sensori**
  Questa configurazione permette di misurare con precisione sia profili che spessori fornendo direttamente in uscita la misura nell'unità ingegneristica desiderata.
- **Funzione di prevenzione delle mutue interferenze**
  Allo scopo di prevenire interferenze tra i due sensori questa serie è equipaggiata con un filtro anti cross-talk (X talk).
- **Ampio set di funzioni**
  Oltre all'alta risoluzione sono disponibili altre potenti funzioni come: selezione del sistema di Misura, selezione del tipo di Guadagno, regolazione del punto Zero, funzione di Offset, funzione di Calibratura della curva di risposta, ecc..
- **Interfaccia RS-232C**
  Tutti i sensori della serie LM300 sono equipaggiati con porta seriale RS-232C. A richiesta sono disponibili anche la porta parallela a 16-bit oppure GP-IB.

SISTEMA DI MISURA



VERSIONI DISPONIBILI

Range misurabile	30 mm		50 mm	
N. di sensori	Versione un sensore	Versione due sensori	Versione un sensore	Versione due sensori
Articolo	ANL3330EC1	ANL3331EC2	ANL3530EC1	ANL3531EC2

All. N°3

CARATTERISTICHE TECNICHE

Punto medio di misura		30 mm		50 mm	
		Versione un sensore	Versione due sensori	Versione un sensore	Versione due sensori
Range misurabile		27÷33 mm		44÷56 mm	
Sorgente luminosa		Diodo laser, lunghezza d'onda 780 nm (durata di impulso 10 µs, 50% duty ratio)			
Classe di protezione del laser		Classe 3B (CENELEC) (Max. uscita 2 mW)			
Uscita di spostamento	Display	-6,5534÷+6,5532 mm		-13,1068÷+13,1064 mm	
	Risoluzione display	0,2 µm		0,4 µm	
	Uscita analogica	±3 V / ±3 mm		±3 V / ±6 mm	
	Risoluz. dell'uscita	0,2 µm		0,4 µm	
	Errore di linearità ★	Max. ±0,1% della Scala Completa			
	Err. di materiale ★★	Max. ±0,3% della Scala Completa			
	Deriva di temperatura	Sensore: max. ±(0,02% della Scala Completa)/C°, Controller: max. ±(0,01% della Scala Completa)/C°			
Tempi di risposta	Frequenza di campionamento	50 kHz	Modo standard 12,5 kHz Modo no crosstalk 6,25 kHz	50 kHz	Modo standard 12,5 kHz Modo no crosstalk 6,25 kHz
	Frequenza di risposta	20 kHz	Modo standard 5 kHz Modo no crosstalk 2,5 kHz	20 kHz	Modo standard 5 kHz Modo no crosstalk 2,5 kHz
	Tempo di risposta	Max. 100 µs = 0,000100 : 10 kHz			
Tempi di misura (da 1 a 2048 volte)		0,02÷40,96 ms	Modo standard 0,08÷163,84 ms Modo no crosstalk 0,16÷327,68 ms	0,02÷40,96 ms	Modo standard 0,08÷163,84 ms Modo no crosstalk 0,16÷327,68 ms
Range di taratura dello zero		±3,0000 mm		±6,0000 mm	
Range di taratura dell'Offset		±3,0000 mm	±3,0000 mm (HEAD1, 2) ±6,0000 mm (ADD, SUB)	±6,0000 mm	±6,0000 mm (HEAD1, 2) ±12,0000 mm (ADD, SUB)
Funzione di No Cross talk		(Non disponibile)	SI	(Non disponibile)	SI
Uscita di allarme		Intensità (DARK, BRIGHT), Range misurabile (FAR, NEAR), Limiti (HIGH, LOW), Uscita transistor: 100 mA, 30 V DC (Collettore aperto)			
Ingressi di controllo		REMOTE INTERLOCK, HOLD, ZERO SET/CLEAR			
Interfacce	Standard	RS-232C (300~19200 bps)			
	Opzionali	GP-IB, parallela a 16 bit			
Grado di protezione (sensore)		IP67 (IEC 144)			
Resistenza alle vibrazioni		da 10 a 55 Hz (1 ciclo/min), doppia ampiezza 0,3 mm (sezione controller), 30 min. sui 3 assi 1,5 mm (sezione sensore), 2 ore sui 3 assi			
Resistenza allo shock		Min. 20G, 3 volte sui 3 assi			
Luminosità ambiente		Lampada ad incandescenza: max. 3000 Lux			
Temperatura ambiente		0 °C÷50 °C			
Temperatura di stoccaggio		-20 °C÷70 °C			
Umidità ambiente		35%÷85% RH (senza condensa)			
Tensione nominale		100÷240 V AC (+10%, -15%)			
Potenza nominale		Max. 50 VA			
Peso (cavo incluso)		Sensore (un sensore) circa 350 g, Controller circa 3,4 kg			

Note: ★ Il valore è riferito ad un oggetto misurato all'interno di un range di ±2 mm per ANL3330EC1/ANL3331EC2 e ±4 mm per ANL3530EC1/ANL3531EC2. L'errore caratteristico di linearità al di fuori di questi range corrisponde all'errore di materiale. Inoltre quando il valore è rappresentato dallo spostamento rispetto alla distanza dal punto medio di misura la formula per l'errore di linearità è:

±3 µm più ±0,1% × Distanza dal punto medio di misura (ANL3330EC1/ANL3331EC2)
±6 µm più ±0,1% × Distanza dal punto medio di misura (ANL3530EC1/ANL3531EC2)

★★ Il valore è riferito al target standard. Inoltre quando il valore è rappresentato dallo spostamento rispetto alla distanza dal punto medio di misura la formula per l'errore di materiale è:

±9 µm più ±0,3% × Distanza dal punto medio di misura (ANL3330EC1/ANL3331EC2)
±18 µm più ±0,3% × Distanza dal punto medio di misura (ANL3530EC1/ANL3531EC2)

Cos'è il TARGET STANDARD? VEDI PAG 99 manuale NAIS

Laser Doppler Displacement Measurement

A Breakthrough In Submicrometer Positioning Technology

by Charles P. Wang

Existing precision displacement-measuring devices are primarily based on linear encoders (optical or magnetic) or laser interferometers. Most encoders use grating scales and frequency counters, while most interferometers use stabilized lasers and fringe counters. In general, interferometers are more expensive and more accurate than linear encoders. However, there are large gaps in price and performance between these two technologies.

Based on current developments in laser radar technology, a new device, a Laser Doppler Displacement Meter (LDDM™) has been developed.[1] This device is an electro-optical assembly, which uses the Doppler shift of a laser frequency caused by the movement of a target to measure displacement accurately over a range of a few meters. As shown in Figure 1, the LDDM consists of a laser head, a retroreflector, a processor (not shown) and a display. Using the latest in microelectronic, electro-optic and optical heterodyning technologies, an LDDM provides a high-precision and low-cost alternative to submicrometer positioning. The key feature of the LDDM is that its performance compares with that of a laser interferometer, while its price compares with that of a linear encoder.

Encoders And Interferometers

A typical linear encoder is an incremental device. It has a series of lines ruled on a scale, either optically or magnetically, and has some type of pickup device that measures the position by counting the number of lines that pass the location of the pickup device. The encoder also typically extrapolates to produce measurement points between the resolution units of the lines.

The basic output of the device is usually a signal corresponding to the output of the detector. To determine which direction the system is running, it is usually necessary to use two or more detectors spaced at some increment apart. An electronic circuit then converts the direct output of the scale into a digital number that corresponds to motion along the axis. Typical accuracy is 10 to 100 parts per million.

As early as 1881, A.A. Michelson employed an interferometer, which now bears his name, to investigate the theory concerning the existence of the "ether." The use of interferometers in length measurement gained significance with the invention of the laser.[2] Basically, as shown in Figure 2, a laser beam is split into two parts of equal intensity by a beamsplitter. One portion is subsequently reflected onto a photodetector via the stationary mirror and the beamsplitter. The second portion of the beam is reflected at the movable mirror, propagates back onto the beamsplitter and is superimposed there over the first portion. These two laser beams generate fringe patterns on the detector. A zero-crossing circuit counts the change in the number of wavelengths of light in the path between the laser and the mirror. It then gives a measurement of the distance the mirror has moved in terms of the number of wavelengths and fractional wavelengths that are counted.

The laser interferometer is an order of magnitude more accurate than the best linear encoders, but its cost is also an order of magnitude higher.

Time-Of-Flight And Chirp Radar Measurements

The time-of-flight technique for distance measurement is very simple. As shown in Figure 3, a laser pulse is launched at time t, and the pulse reflected by a target at a distance D, will reach the detector at time t + T. D then equals cT/2, where c is the speed of light. For high accuracy, the pulsewidth should be small and the repetition rate should be high. However, the repetition rate is limited by the range of the two-way transit time T, so the repetition rate is less than 1/T. Otherwise, it is difficult to keep track of which return pulse corresponds to which output pulse.

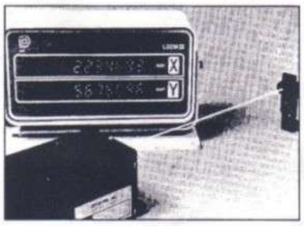


Figure 1. The Laser Doppler Displacement Meter.

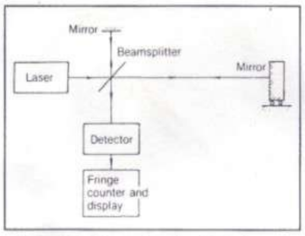


Figure 2. Schematic of a Michelson interferometer.

To break this barrier, it is conceivable to mark the output pulse by different frequencies. That is, use a pulse train of different frequencies, so that the corresponding output pulses and return pulses can be tracked. Hence, the repetition rate can be increased M times, where M is the number of different frequencies of the output pulses.

Since the output pulse and return pulse can be identified by their frequencies, a continuous wave-train with variable frequency can be used to determine the distance. Furthermore, heterodyne techniques can be used to determine the frequency difference that corresponds to the two-way transit time, as shown in Figure 4. Here, the distance can be expressed as:

$$D = cT/2 = (c\Delta f/2)/(df/dt), \qquad (1)$$

where Δf is the beat frequency and (df/dt) is the chirp rate. This technique is commonly known as a chirp radar.

Charles Wang is president of Optodyne, Inc., Compton, Calif.

Reprinted from Lasers & Optronics, September 1987 issue, pages 69-71.

All. N°4

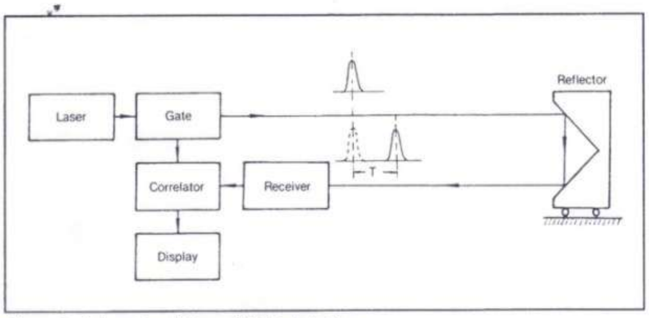


Figure 3. Schematic of time-of-flight detection.

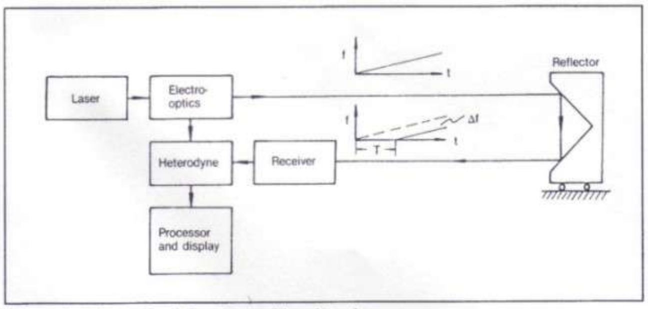


Figure 4. Schematic of frequency chirp detection.

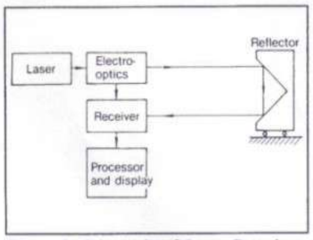


Figure 5. Schematic of Laser Doppler Displacement Meter.

Displacement Measurement By Doppler Effect

The LDDM is based on the principles of radar, the Doppler effect and optical heterodyning. Similar to a Doppler radar, a target (here, a retroreflector) is illuminated by a laser beam as shown in Figure 5. The light reflected by the retroreflector is frequency-shifted by the motion of the retroreflector. The Doppler frequency shift can be expressed[3] as:

$$f = \frac{2f_0}{c} v \qquad (2)$$

or

$$\frac{\Delta\phi}{2\pi} = \frac{2f_0}{c} \Delta z, \qquad (3)$$

where f and Δφ are the frequency and phase shift, respectively; v and Δz are the velocity and displacement of the retroreflector, respectively; f_o is the frequency of the laser; and c is the speed of light.

A phase detector measures the phase variation, which corresponds to the displacement of the retroreflector. When the displacement is larger than the half-wavelength, λ/2, a counter records the total phase changes. That is,

$$\Delta\phi_{total} = 2\pi N + \phi, \qquad (4)$$

where N is the number of half-wavelengths and φ is the phase angle less than 2π. The total displacement, Δz, can be expressed as:

$$\Delta z = \frac{c}{2f_0} (N + \phi/2\pi). \qquad (5)$$

A microprocessor is used to read the counter and the phase angle; convert them to inches or centimeters of travel; control the ten-digit display; compensate for the change in light speed caused by temperature, pressure and humidity variations; and communicate with an external computer or controller.

The resolution of the device is the minimum detectable phase φ, which is limited by the electronic signal-to-noise ratio and the root-mean-square phase noise. The maximum velocity, or slew rate, is determined by the bandwidth of the phase detector and the counter. For a typical LDDM, the bandwidth is 3 megahertz, which corresponds to a maximum velocity of 36 inches per second (or 50 meters per minute).

Note that in Equation 5, the N and φ are two different terms; hence, high resolution and high maximum velocity could be obtained at the same time. In a typical interferometer, however, higher resolution is obtained by dividing the wavelength or doubling the number of counts. Hence, higher interferometric resolution can only be achieved at lower maximum velocity.

Accuracy And Resolution

The accuracy of the LDDM can be expressed[4] as:

$$\frac{\Delta z}{z} = \pm \frac{\Delta n}{n} \pm \frac{\Delta\lambda}{\lambda} \pm \frac{(<\Phi_n^2>)^{1/2}\,\lambda}{4\pi \quad z} \pm \theta_r^2 \qquad (6)$$

where Δz/z is the accuracy expressed as the ratio of maximum error and the total displacement; n is the refractive index of air; λ is the laser wavelength; $(<\Phi_n^2>)^{1/2}$ is the rms electronic noise; and θ is the misalignment angle.

The refractive index of air varies with temperature, pressure and relative humidity. At visible wavelengths,

$$n - 1 = 10^{-6} (79/T) (P + 4800\, e/T), \qquad (7)$$

where T is the temperature (Kelvin), P is the pressure (millibars) and e is the vapor pressure (millibars).

As a rule of thumb, a one-degree-Kelvin increase in temperature corresponds to an increase of the laser wavelength of 1 part per million. A one-degree-Kelvin increase in temperature is equivalent to a 3.3-mbar decrease in pressure or a 25-percent decrease in relative humidity. Thus, for accurate displacement measurements, temperature, pressure and relative humidity should be measured and their effect compensated by using Eq. 7.

The laser wavelength may be changed by thermal expansion and mechanical vibration of the resonator. In general, the gain bandwidth of a helium-neon laser is approximately 1 gigahertz. The output frequency of the laser is determined by the separation of the resonator mirrors. Laser frequency can be stabilized by adjusting the resonator length, either by controlling the tube temperature or by using a piezoelectric-controlled resonator mirror.

Laser frequency stabilities of better than 10^{-11} have been achieved. Frequency-stabilized HeNe lasers based on the transverse or longitudinal Zeeman effect, the intensity ratio of two longitudinal modes, an absorption cell, a temperature sensor, and a reference quartz cell are commercially available. Their frequency stabilities range from 10^{-7} to 10^{-9}.

For a free-running HeNe laser, the frequency stability is roughly 10^{-6}. Because of this property, the National Bureau of Standards has concluded that physical principles of laser action preclude a HeNe laser from producing light of a wavelength that differs from the accepted value by more than 1 ppm. Hence for all technical purposes, a HeNe laser that produces a beam realizes the international and U.S. standard of length to an accuracy sufficient to the needs. NBS also considers all such devices traceable to national standards in all the usual contexts.

The dominant electronic noise is the phase noise induced by photodetector shot noise. The mean squared phase noise is:

$$\begin{aligned} <\Phi_n^2> &= <i_n^2>/<i_h^2> \\ &= 2eB\,(<i_d>/<i_h^2>) \end{aligned} \qquad (8)$$

where $<i_n^2>$ is the mean squared detector noise current, e is the electron charge, i_d is the detector cathode current, B is the filter bandwidth, and i_h is the optical heterodyne current.

For a typical LDDM using a 0.5-milliwatt HeNe laser and a 4-MHz bandwidth, the rms phase noise is less than 10^{-3}, which corresponds to a resolution of 0.3 nm.

The fourth term of Eq. 6 is the error due to misalignment, commonly known as cosine error. For an accuracy of 1 ppm, the misalignment angle must be limited to less than 1 milliradian.

Other error sources are laser mode hopping; the position change of the laser beam, detector and optical components due to mechanical vibration and thermal stability; and radio frequency interference and noise pickup. All of these could be minimized by proper design and proper installation of the instrument.

Conclusion

A laser Doppler displacement meter offers a number of attractive benefits to submicrometer positioning. First, it can use any continuouswave laser with a reasonable frequency stability. Second, it requires no optical feedback or interference to the laser resonator; the electro-optical device acts as an optical isolator, preventing stray light from the target from entering the laser resonator and disturbing the laser's frequency stability. Third, the entire system is compact and easy to align. The interior of the laser head box is kept at a constant temperature to reduce thermal distortion of the optical components. Fourth, high maximum velocity (slew rate) and high resolution are simultaneously attainable.

> In general, interferometers are more expensive and more accurate than linear encoders.

Applications for such a device include x-y stages, pattern generators, steppers and aligners, magnetic and optical disk drives, diamond-point turning machines, precision machine tools, computer-numerical-control machines and coordinate-measuring machines.

References

1. C.P. Wang, "Laser Doppler Displacement Measuring System and Apparatus," U.S. Patent pending. 2. J. Berger and R.H. Lorberg, "A Laser Earth Strain Meter," Rev. Sci. Instrum. **40** (12):1569-1575 (Dec 1969). 3. C.P. Wang, "Laser Anemometry," *American Scientist* **65** (3):289-293 (May-Jun 1977). 4. C.P. Wang, R.L. Varwig and P.J. Ackman, "Measurement and Control of Subangstrom Mirror Displacement by Acousto-optical Technique," *Rev. Sci. Instrum.* **53** (7):963-966 (Jul 1982).

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Using the Laser Doppler Displacement Meter For Precision Positioning And Motion Control

By Charles P. Wang, Optodyne, Inc., Compton, Calif.

Precision positioning and motion control are important for high accuracy linear or XY-stages. To achieve submicron tolerances and high speed motion on a linear or XY-stage is in increasing demand, particularly in IC manufacturing, video inspection, coordinate measuring machines and machine tools. A constant concern is maintaining the structural integrity of a complex stage or machine.[1] Lead screw nonuniformity and thermal expansion can be minimized by using a linear encoder. However, the effects of thermal gradients and their changes cause twisting and bending of structures, which can lead to angular motions and large Abbe offset errors.[2]

Also, because of the high pulse rates associated with high resolution positioning, the maximum speed of motion has to be reduced. For example, at 0.1 microinch resolution and 96 ips, the pulse rate is 960 MHz, which is beyond the capability of most servo controls.

However, a new type of position sensor, the laser doppler displacement meter (LDDM)[3], can provide both linear and angular measurement simultaneously, and both high resolution and low resolution positioning information simultaneously. By using the LDDM, Abbe error can be minimized and both high resolution and high speed motion of a linear or XY-stage can be achieved.

Laser Doppler Displacement Meter

The LDDM is based on the principles of radar, the Doppler effect and optical heterodyne. Basically, a target or retroreflector is illuminated by a laser beam. The laser beam reflected by the retroreflector is frequency shifted by the motion of the retroreflector, and the phase of the reflected laser beam is proportional to the position of the retroreflector. That is,

$$x = \frac{c}{2f}\left(N + \frac{phi}{2\pi}\right) \qquad (1)$$

where x is the position of the retroreflector, c is the speed of light, f is the laser frequency, N is the number of 2πs, and phi is the phase angle. For a typical output, N is expressed as the quadrature square waves and phi is expressed as the analog signal shown in figure 1. The maximum speed for the phase detection is 8 MHz, which corresponds to 96 ips (2.5 m/s), and the maximum resolution using an 8-bit ADC is 0.05 microinch (1.2 nm).

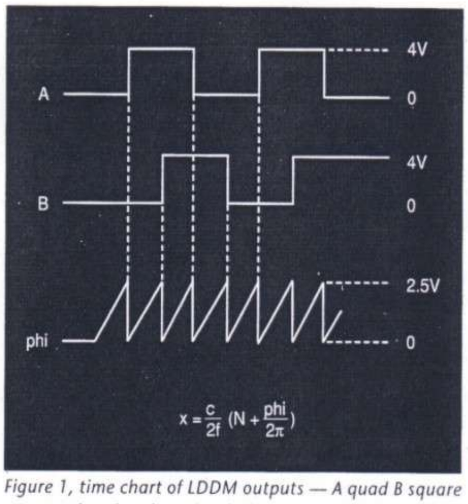
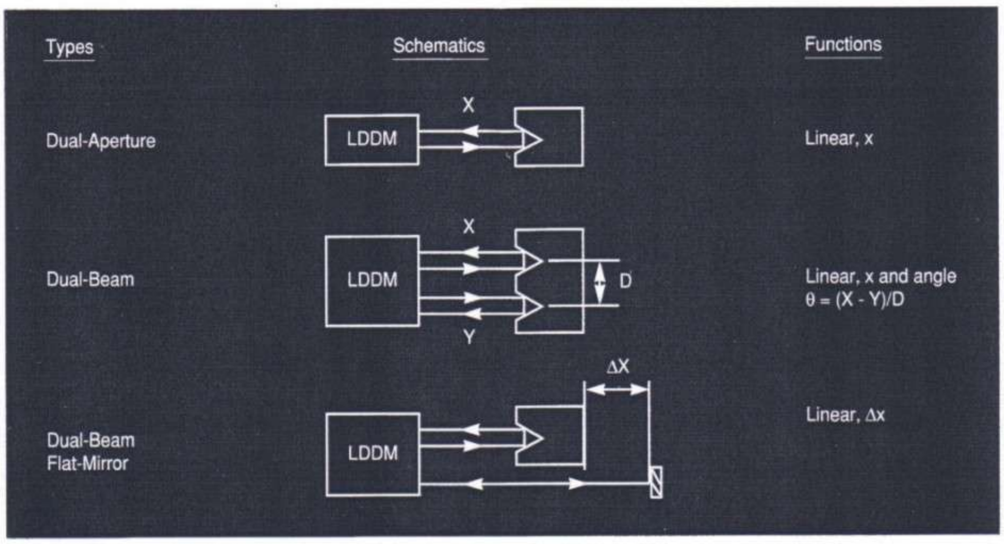


Figure 1, time chart of LDDM outputs — A quad B square waves and analog phase signal.

For motion control there are three types of laser heads: dual-aperture, dual-beam and dual-beam flat-mirror. As shown in table 1, for the dual-aperture laser head, there is an exit aperture for the output laser beam, a receiving aperture for the return laser beam, and a corner-cube used as a retroreflector. For the dual-beam laser head, there are two exit laser beams, two return laser beams, and two corner-cubes. The separation for the two corner-cubes or laser beams is D. Using a two-axis processor module, the outputs are the displacement x and the angular angle theta, which can be expressed as (X-Y)/D. For the dual-beam flat-mirror laser head, the first exit, return laser beam, and the corner-cube are the same as in the dual-aperture laser head. However, the second laser beam shares the same aperture for exit beam and return beam, and the retroreflector is a flat mirror. The output of the laser head is the difference of the displacement between the corner-cube and the flat-mirror. This eliminates any error caused by the mechanical motion and air current between the corner-cube and the laser head. Hence, higher accuracy can be achieved.



Types	Schematics	Functions
Dual-Aperture	LDDM X	Linear, x
Dual-Beam	LDDM X Y D	Linear, x and angle $\theta = (X - Y)/D$
Dual-Beam Flat-Mirror	LDDM ΔX	Linear, Δx

Table 1, types of LDDM laser heads.

The major features of the LDDM are that it provides both quadrature signal and analog signal, and measures both displacement and pitch angle (or yaw angle). As a result, high maximum velocity, high resolution and high positioning accuracy are simultaneously attainable. Other features are:

- no need for a complex interferometer,
- no need for expensive optical components,
- no serpentine error,
- no interpolation error, and
- compactness and simplicity.

Applications

A typical application in a linear measuring device is shown in figure 2. Here a dual-beam laser head is used. Both displacement and pitch angle can be measured. The true dimension L can be expressed as:

$$L = X - d \bullet \text{theta} \qquad (2)$$

where X is the measured displacement, d is the distance between the measuring axis and the anvils, and theta is the measured pitch angle. Hence, the true dimension L can be obtained even without extremely accurate guideways and a heavy and stable structure.

A typical application in a precision XY-stage is shown in figures 3a and 3b. Here two dual-beam flat-mirror laser heads are used to measure X and Y motions. Mount both the x-axis corner-cube and the y-axis corner-cube on the camera or lens holder as references, and both the x-axis flat-mirror and y-axis flat-mirror on the XY-stage. The position of the XY-stage with respect to the camera holder can be determined and both dead path error and Abbe error are minimized.

A typical application in a high speed and high resolution XY-stage is shown in figures 4a and 4b. For simplicity in illustration, only the x-stage is shown. Here a two-loop servo control is used. A DC motor is used for fast and coarse control and a piezoelectric translator (PZT) is used for fine control. The PZT has a unique ability to convert electric energy directly into mechanical movement with high resolution. The PZT effect is non-linear with hysteresis and slow creeping. However, the PZT is used here only as a driver, therefore the position accuracy is determined by the accuracy of the

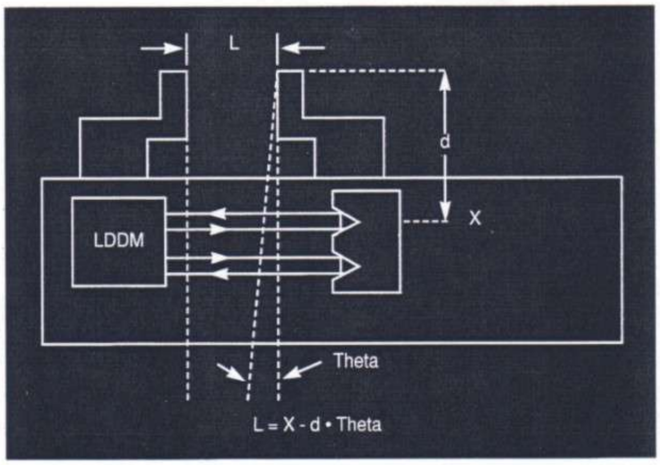


Figure 2, a schematic of a linear measuring device. Here the true dimension L is determined by the measured X and theta. Hence, the straightness of the guideway and rigidity of the structure become less important.

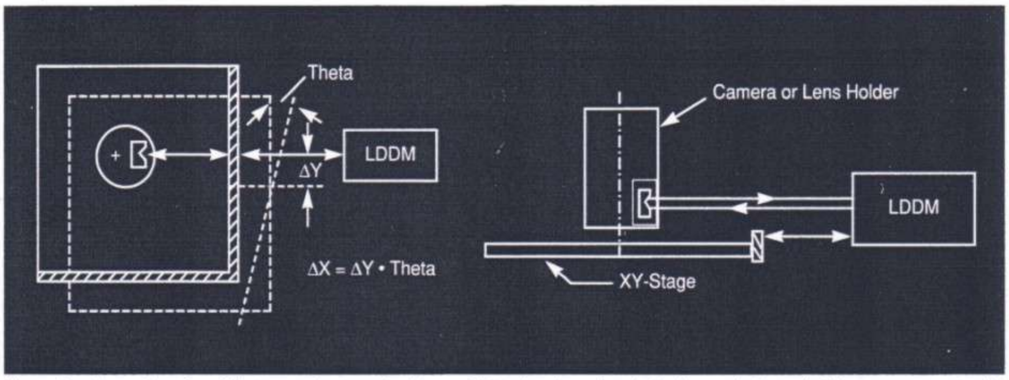


Figure 3, schematics of an XY-stage using two dual-beam flat-mirror laser heads (only one is shown). This arrangement minimizes the dead path and Abbe error. Figure 3a (left) shows how Abbe error due to yaw motion is minimized and figure 3b (right) shows how the dead path error is minimized.

LDDM.

The coarse loop, using the A quad B output from the LDDM, can move the stage to a position within 12.5 microinch from the targeted position. The fine loop, using the analog phase output from the same LDDM, can further move the stage to a resolution of 0.1 microinch. This configuration allows both high speed, up to 96 ips, and high resolution, up to 0.1 microinch, to be achieved.

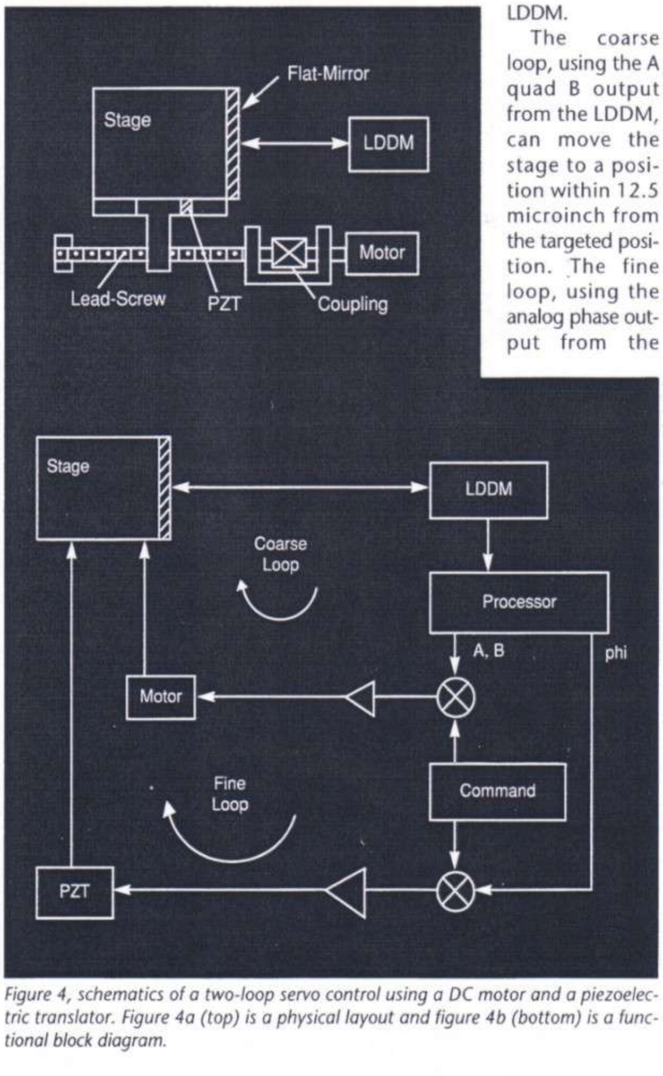


Figure 4, schematics of a two-loop servo control using a DC motor and a piezoelectric translator. Figure 4a (top) is a physical layout and figure 4b (bottom) is a functional block diagram.

Conclusion

Through using the LDDM both linear and angular motion, and both high speed and high resolution motion control can be achieved. Usually, to achieve high speed and high precision positioning, very difficult and expensive mechanical solutions are required. However, because of the recent developments in microelectronics, digital electronics and electro-optics, the electro-optical solutions are relatively easy and low cost.

References

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3. C.P. Wang, "Laser Doppler Displacement Measurement," *Lasers & Optronics*, 6 (No. 9), pp. 69-71, Sept. 1987.

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Accelerometer Calibration Using a Laser Doppler Dispacement Meter

Wayne Tustin, Equipment Reliability Group, Mesa, Arizona
Felix Lin, Optodyne, Inc., Compton, California

What is Acceleration? Figure 1 illustrates classical sinusoidal vibration, with instantaneous single-frequency vibratory displacement x, velocity v and acceleration a, all plotted on a common time base. Note that v is the time derivative, the rate of change of displacement with time, the slope of the displacement vs. time graph. Note also that a is the next time derivative, the rate of change of velocity with time, the slope of the velocity vs. time graph.

Figure 1 can be summarized by three equations:

$$x = X \sin 2\pi ft$$
$$v = x = 2\pi f X \cos 2\pi ft$$
$$a = v = x = -4\pi^2 f^2 X \sin 2\pi ft$$

If one wishes the details of a vibration time history (comparable to Figure 1), an analog or digital oscilloscope or recording oscillograph is useful. However, few requests for vibration and shock data specify the time history. Most specify some statistical measure such as the peak value (comparable to X) or the root mean square (RMS) value.

The maximum values of the above three equations are observed at a moment when the sine or cosine term equals unity, so that:

$$X = X$$
$$V = 2\pi fX$$
$$A = 4\pi^2 f^2 X$$

Only rarely are metrologists asked for X, the zero-to-peak displacement. They are usually asked for D, the peak-to-peak displacement. Since $D = 2X$, the three equations change to:

$$D = 2X$$
$$V = \pi fD$$
$$A = 2\pi^2 f^2 D$$

X and D can be stated in in. or mm, V in in/sec or mm/s and A in in/sec^2 or mm/sec^2. Divide A by 386 in/sec^2 or 981 mm/sec^2 to get A in multiples of the earth's gravitational constant.

Displacements Tiny at High Frequencies. In theory, if we can accurately measure X or D or V or A, and if all waveforms are sinusoidal, we can calculate the other terms. However, a serious problem exists at higher frequencies, where the displacement values X and D tend to be very small. For example, if we decide to sinusoidally shake an accelerometer at a peak acceleration $A = 10$ g at a frequency of 1,000 Hz, our peak-to-peak displacement $D = 0.0002$ in. ≈ 0.005 mm. At a frequency of 2,000 Hz, D will be only 1/4 as large. At a frequency of 20,000 Hz, D will be only 1/400 as large, ≈ 0.5 μin. or 0.0125 μm.

How can we accurately read such a small dynamic displacement? A microscope? A typical 50X microscope with calibrated reticle is somewhat useful for an absolute accelerometer calibration around 50 Hz, with acceleration $A = 10$ g, displacement D ≈ 0.08 in. ≈ 0.2 mm. But it is useless at 1000 Hz with a D of 0.0002 in. or 0.005 mm.

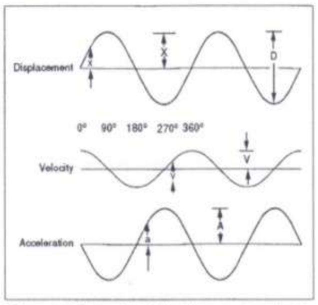

Figure 1. Sinusoidal displacement, velocity and acceleration time histories.

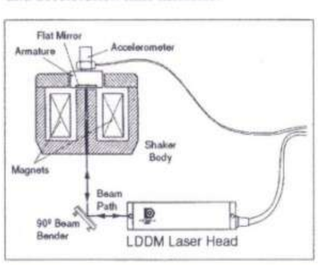

Figure 2. An accelerometer is mounted on the armature of an electrodynamic shaker. A horizontal laser beam from the LDDM hits the 45° × 45° mirror, and is then reflected up to a flat mirror on the bottom of the shaker armature and back to the LDDM via the 45° mirror.

Consequently, most laboratories and their clients have in past years settled for comparison calibration. Comparison calibration at The National Institute for Standards and Technology (NIST) is very accurate, with ±1% uncertainty. However, subsequent comparison calibrations against transfer standards, (each of which contributes uncertainty), is seldom better than ±2%. Subsequent calibrations of working accelerometers (each of which contributes still more uncertainty) is seldom better than ±2%. When this is added to the uncertainties of ancillary equipment and usage, uncertainties are seldom better than ±5%.

Need for Accelerometer Calibration. Accelerometers and accompanying signal processing and readout functions should be recalibrated on schedule, typically every six months. They should also be recalibrated before (and immediately after) important vibration and shock investigations and tests. Accelerometers should also be checked immediately if struck or dropped.

Absolute vs. Comparison Calibration. Metrologists prefer absolute calibration for its greater accuracy. Unfortunately, absolute calibration of accelerometers above 40 to 50 Hz has been difficult. Absolute calibration is based upon the primary standards of mass, time and length maintained in the USA by NIST, in the UK by NPL (National Physical Laboratory), in Germany by PTB (Physikalisch-Technische Bundesanstalt), etc.

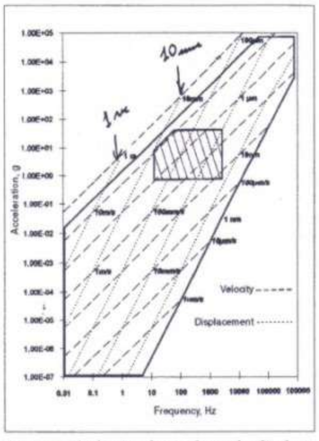

Figure 3. The large polygon shows the displacement, velocity and acceleration levels which the LDDM can measure in one large dynamic range (no switching required). The smaller polygon shows the displacement, velocity and acceleration levels demanded by typical vibration testing specifications. A range of constant-velocity lines assists the reader in evaluating any maximum or minimum velocity limitations imposed by the instrument.

Imagine that you are holding a "standard" accelerometer, just recalibrated at a facility once or twice removed from NIST's ±1% uncertainty. Its sensitivity is known in picocoulombs per g, but with an uncertainty of perhaps ±2%. If you now calibrate the test accelerometer by the usual "comparison" route, you will mount the test accelerometer and standard accelerometer back-to-back on a suitable fixture driven by an electrodynamic shaker. You will compare their electrical outputs over the needed range of frequencies and accelerations:

$$V_s = S_s a \text{ and } V_t = S_t a$$

where V = accelerometer output voltage, S = accelerometer sensitivity, and a = the applied acceleration for the standard and test accelerometers. Assuming that the accelerations are equal:

$$V_s/V_t = S_s/S_t$$

Since S_s is known, you can calculate S_t with a possible uncertainty of ±2.5%:

$$S_t = S_s V_t / V_s$$

There are at least three sources of error in this procedure: 1. error in the "known" sensitivity of the standard accelerometer; 2. errors in measuring signals V_s and V_t; and 3. Slight differences in the motion of the two accelerometers. These errors can always be reduced somewhat, but we recommend that you avoid them entirely by switching to absolute calibration.

Lasers to the Rescue. Fortunately, laser technology now makes it possible to accurately read peak-to-peak displacement D on the order of 0.05 μin. or 1.2 nm (see Figures 2 and 3). Thus the frequency of absolute accelerometer calibration can be greatly extended. Notice the larger shaded area of Figure 3 and compare it with the much smaller area demanded by typical vibration testing specifications.

The Optodyne LDDM measures phase shift (between the outgoing and the return laser light beams of Figure 2). This phase shift develops an electrical signal that is proportional to vibratory (or transient) displacement. The LDDM is thus distinctly different from laser velocimeters and vibrometers (LDV), which develop an electrical signal (must be averaged over time) that is proportional to vibratory velocity (must be above the LDV's minimum velocity). LDV signals must be electrically integrated to obtain displacement. The LDDM can measure smaller displacements, and with more favorable signal/noise ratios than the LDV.

Rather than compare with NIST's mass (not needed here), time and length standards, Optodyne uses a crystal-controlled clock as a fundamental frequency standard. Optodyne's length standard is based on a laser whose wavelength is checked against an NIST standard.

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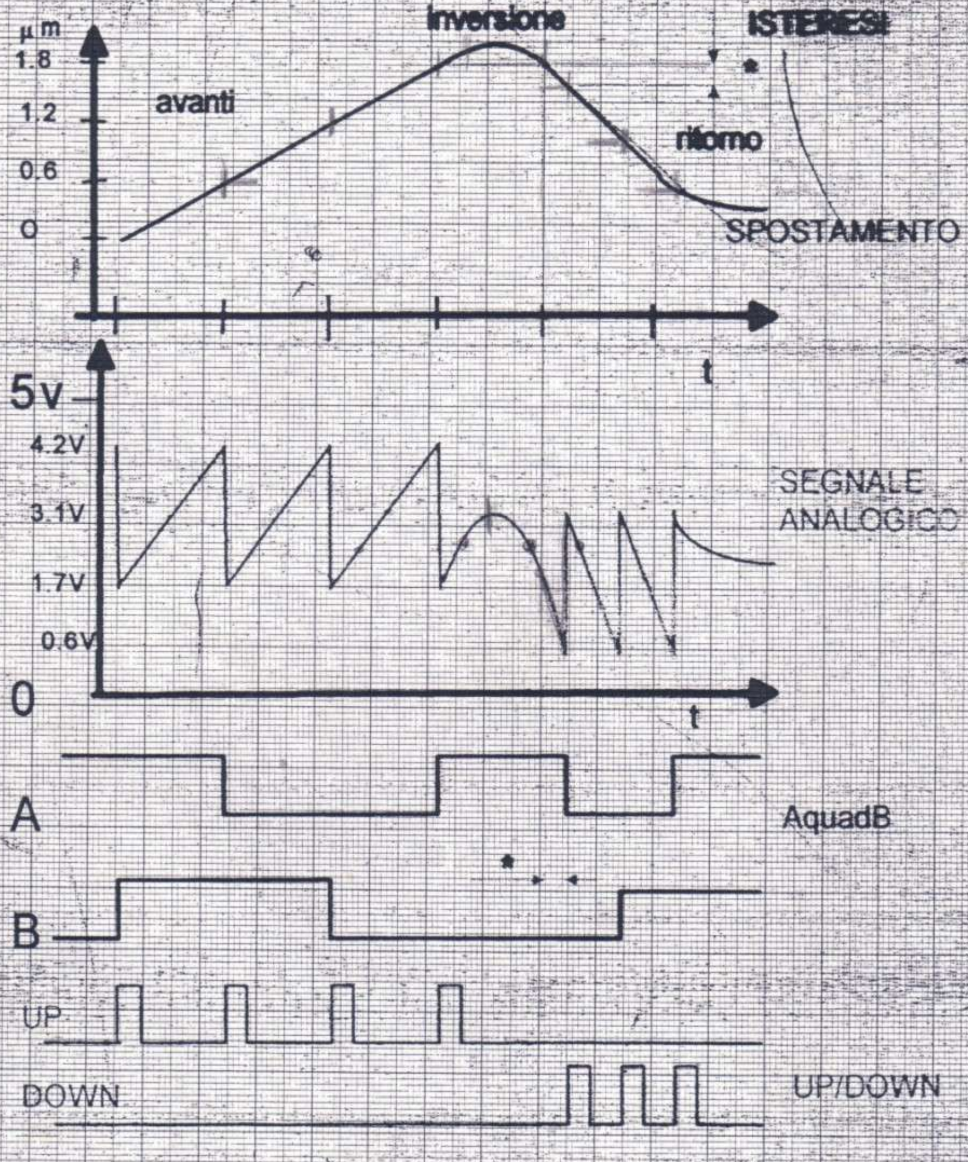
SEGNALI DI USCITA



Esempio di segnale analogico associato a segnale incrementale nella forma AquadB o UP/DOWN.

Quando il segnale analogico raggiunge il valore massimo, positivo o negativo, scatta un conteggio mentre il segnale analogico torna al lato opposto della sua banda di variazione.

YOU & YEW
Both Winners

3655
ANALYZING RECORDER

All. N°5

YEW
YOKOGAWA HOKUSHIN ELECTRIC

designated by the SET REF key can be displayed in digital.

Scaling: Scaling is possible in PROGRAM (X-Y) mode.

Plotting

Plot Formats: CRT Copy, Analog, Digital and List (program list printout).

Title Plotting: Waveform title (alphanumerics, parentheses, +, −, ×, ÷) can be entered and plotted by using programming keys.

Maximum Plotting Area: A4 size (CRT Copy mode), or continuous (Analog or Digital mode).

Duplex Plotting: One or more measured data (waveforms) can be superimposed over an initial plot.

Automatic Plot Start: Plotting is automatically initiated by the trigger.

REAL-TIME MODE

Measurement Channels: All input channels (real-time display).

Plotting Mode: ANA/DIG... printout of analog data (150 mm width, continuous), and digital data (date, time, chart speed and measured data at 40 mm intervals).

Sampling Interval: 1 s on analog (without computation).

Chart Speeds: 1, 2, 4 cm/min, 1, 2, 4, 8, 10, 20, 40 cm/h.

Accuracy of Chart Speeds: ±0.2%

Computing Functions: Same as Computing Functions in Memory Mode except for MEAN.

Common Mode Rejection (Typical): 120 dB at 50 or 60 Hz.

Normal Mode Rejection (Typical): 50 dB at 50 or 60 Hz.

GENERAL SPECIFICATIONS

Display Tube: 7 inch CRT (amber), 640 × 200 resolution.

Plotter: Four-color digital plotter using ball-point pens (water ink of black, red, green and blue), maximum pen speed... 200 mm/s on analog, approx. 8 characters/s on digital, resolution... 50 μm.

Battery-Backup Memory: Three internal batteries maintain eight programming modes when power is removed (battery life is approx. one year).

Accuracy of Internal Clock: Approx. 50 ppm (typical), clock is maintained for 36 hours after power off.

Operating Temperature Range: 5 to 40°C (41 to 104°F).

Humidity Range: 40 to 80%, relative humidity (non-condensing).

Dielectric Strength: 1,500 V AC for one minute between power line and case, 1,000 V AC for one minute between input terminals and case.

Insulation Resistance: More than 10MΩ at 500 V DC between power line and case, and between input terminals and case.

Power Requirements: 90 to 132 V, or 180 to 250 V AC (must be specified), 48 to 63 Hz.

Power Consumption: 240 VA max.

Dimensions: Approx. 400 (W) × 236 (H) × 499 (D) mm, 15-3/4 × 9-3/8 × 19-5/8".

Weight: Approx. 17 kg (37.5 lbs)... 2-channel model, 18 kg (39.7 lbs)... 4-channel model.

Accessories supplied at no extra cost: Power cord... 1 set, roll chart... 1 roll, ball-point pens... 4 pcs. (black, red, green, blue), chart roller... 1 pc., chart guide... 1 set, fuse... 1 pc., batteries (SUM-3)... 3 pcs., dust cover... 1 pc.

OPTIONAL FUNCTIONS

FFT Module (365920A)

Analyzing Functions: Linear spectrum, power spectrum, RMS spectrum, cross spectrum, transfer function, and coherence function.

Dynamic Range: 72 dB (typical).

Number of Channels: Up to 2 (any 2 channels for 4-channel model).

Frequency Range: 50 Hz, 100 Hz, 200 Hz, 500 Hz, 1 kHz, 2 kHz, 5 kHz, 10 kHz, and 20 kHz.

Data Sampling: 512 points.

Frequency Resolution: 1/200 of analyzing frequency range.

Sampling Frequency: 2.56 times of analyzing frequency range.

Accuracy of Frequency Axis: ±0.02%.

Weighting: Hanning or rectangular window.

Anti-Aliasing Filter: 120 dB/oct. (typical), or OFF.

Triggering: Same as in Memory Mode.

Averaging Modes: Linear sum (stable), or exponential averaging for time and frequency domain, and peak hold for frèquency domain (number of averages... 4, 8, 16, 32, 64, 128 or 256 times, preselectable).

Display Format: Dual, single, Nyquist diagram, or Array (32K-data model).

Data Memory Module (365910B)

Memory Capacity: Approx. 32 K data.

File Management: Directory.

Data Storage: Up to 16 files, selectable for any portion of data butter memory.

Battery-Backup Memory: Three 1.5 V batteries (AM-4) maintain all stored data when power is removed (battery life is approx. one year).

GPIB Interface (3655□□/GP-IB)

Functional, Electrical and Mechanical Specifications: Meets the IEEE Standard 488-1978 "Digital Interface for Programmable Instrumentation", interface function and identification... SH 1, AH 1, T 6, L 4, SR 1, RL 1, PP 0, DC 1, DT 1, C 0.

Controller Interface Functions: Start, Stop, Progam Start, Plot Start, and others can be remotely controlled. Measured data and computed data can be transferred to a controller by ASCII or binary data code.

Note: GPIB should always be ordered together with the basic instrument since the combination instrument will be tested at YEW.

Specifications

INPUT

Voltage Input

Input Channels: Up to 2 or 4.

Measuring Ranges: ±60 mV, 200 mV, 600 mV, 2 V, 6 V, 20 V, 60 V full scale.

Type of Input: Floating (unbalanced), isolated for each channel.

Input Impedance: Approx. 1 MΩ.

Input Coupling: DC or AC (DC only in Real-Time Mode).

Maximum Allowable Input Voltage: 130 V DC + ACpk.

Frequency Band: DC to 20 kHz (−3dB, DC coupling), 1 Hz to 20 kHz (−3dB, AC coupling), at preamplifier filter OFF.

Basic Accuracy: ±0.25% of full scale at 23±3°C on 2 V range.

Error between Ranges: Less than ±0.25%.

Bias Current: 2nA (typical).

Temperature Coefficient: Zero drift... automatically calibrated at the start of measurement, gain... 0.01%/°C, or 0.05%/°C at anti-aliasing filter ON.

Input Voltage Monitor: 13-level LED display.

Temperature Input (not including FFT mode)

Measuring Ranges and Accuracy: ANSI, JIS model...

Range		Accuracy
R	0 to 1,600°C	0 to 200°C; ±6°C, 200 to 800°C; ±4°C, 800 to 1,600°C; ±(0.25% of rdg + 2°C)
K	−200 to 1,300°C	−200 to 0°C; ±(1% of rdg + 2°C) 0 to 1,300°C; ±(0.25% of rdg + 2°C)
E	−200 to 800°C	−200 to 0°C; ±(1% of rdg + 1.5°C) 0 to 800°C; ±(0.25% of rdg + 1.5°C)
J	−200 to 900°C	−200 to 0°C; ±(1% of rdg + 1.5°C) 0 to 900°C; ±(0.25% of rdg + 1.5°C)
T	−200 to 400°C	−200 to 0°C; ±(1% of rdg + 1.5°C) 0 to 400°C; ±(0.25% of rdg + 1.5°C)

DIN model...

Range		Accuracy
PtRh-Pt	0 to 1,600°C	0 to 400°C; ±5°C 400 to 1,600°C; ±(0.25% of rdg + 3°C)
NiCr-Ni	−200 to 1,300°C	−200 to 0°C; ±3°C 0 to 1,300°C; ±(0.25% of rdg + 2°C)
ANSI E	−200 to 800°C	−200 to 0°C; ±3°C 0 to 800°C; ±(0.25% of rdg + 2°C)
Fe-CuNi	−200 to 900°C	−200 to 0°C; ±3°C 0 to 900°C; ±(0.25% of rdg + 2°C)
Cu-CuNi	−200 to 400°C	−200 to 0°C; ±2°C 0 to 400°C; ±(0.25% of rdg + 1.5°C)

at 23±3°C, line filter ON, not including reference junction compensation error.

Compensation Error: ±0.8°C.

A-D Conversion (for each channel)

Resolution: 14 bits.

Conversion Speed: 20μs.

MEMORY MODE

Memory

Memory Capacity: 8 K data/channel **(3655☐1)**, or 32 K data/channel **(3655☐2)**.

Data Buffer Memory: 500, 2 K, *8 K data **(3655☐1)**, or 500, 2 K, 8 K, *32 K data **(3655☐2)**, *...Not including computing or averaging operation.

Writing Rate: 20, 50, 100, 200, 500 μs, 1, 2, 5, 10, 20, 50, 100, 200, 500 ms, 1 s/data, or external clock.

Timebase Accuracy: ±0.02%.

Pre-Trigger: 0 to 100%, selectable in 10% steps.

Triggering

Trigger Modes: FREE RUN... automatically updates memory data by internal trigger, REPEAT... continuously updates memory data by trigger, SINGLE... store measured data of one sweep by trigger.

Trigger Source: Internal (CH A, CH B, CH C, CH D) or external (TTL-level).

Trigger Slope: Positive (+) or negative (−) slope, selectable.

Trigger Level: −100 to +100% (internal), TTL-level (external).

Averaging: Linear sum (stable), or exponential averaging (number of averages... 4, 8, 16, 32, 64, 128 or 256 times, preselectable).

Filter

Cut-Off Frequency (−3 dB): 1.5 Hz (line), 50, 100, 200, 500 Hz, 1, 2, 5, 10, 20 kHz, or OFF (anti-aliasing).

Filter Characteristics (Typical): 1.5 Hz... −50dB at 50 or 60 Hz, other ranges... 120 dB/oct.

Computing Functions

Operational Modes: +, −, ×, ÷, SQR (square root), LOG (logarithm), EXP (exponential function), ABS (absolute value), and MEAN (100-point moving average).

Computing Modes: Data computation between channels, setting of constant and engineering units.

Display

Display Format: Single mode... 1, 2, 3 or 4 woveforms on a single coordinate (Y-T), dual mode... 1 or 2 waveforms each on dual coordinates (Y-T), X-Y mode... X-Y display ot 1 channel (X axis) and other 1 to 3 channels (Y axis).

Zooming: Vertical (Y axis on Y-T or X-Y mode, X axis applied on X-Y mode)... waveform identified by the cursor can be zoomed in at a magnification factor of 2, 4, 8, 16, 32 or 64. Horizontal (T axis on Y-T mode)... all displayed waveforms can be zoomed in at the following magnification factors:

Buffer memory setting	Factor
500 data	2, 4, 8
2 K data	2, 4, 8, 16, 32
8 K data	2, 4, 8, 16, 32, 64, 128
32 K data	2, 4, 8, 16, 32, 64, 128, 256, 512

Scroll: All displayed waveforms can be scrolled in the time axis direction by pressing the SCROLL key (Y-T mode).

Cursor: Y-T or X-Y data of any waveform identified by the cursor can be displayed in digital.

Reference Cursor: Deviation between two points

LONG STROKE SHAKER

30-lb force
30-in/s velocity
6.25-in p-p stroke

Model 113

ELECTRO-SEIS®

The APS 113 **ELECTRO-SEIS®** is a force generator specifically designed to be used alone or in arrays for studying dynamic response characteristics of various structures in the seismic frequency range. It finds use in forced excitation of complex structures such as piping systems, electrical substation structures and apparatus, towers, floors, bridges, missiles, aircraft, spacecraft, etc.

APPLICATIONS

- Determination of natural mode frequencies, shapes, damping ratios, and stress distributions
- Excitation of manufactured equipment in the factory or installed in the field to demonstrate compliance with seismic specification criteria
- Excitation for transmissability measurements
- Seismic simulation for components
- Calibration and test for seismic instruments

FEATURES

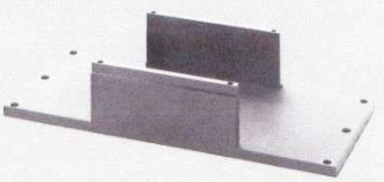
- ☐ Generates sinewave, swept sinewave, random or impulse force waveforms, fully adjustable at source.
- ☐ Test set-up flexibility — operates fixed body, free body, free armature
- ☐ Optimized to deliver power to resonant load with minimum shaker weight and drive power
- ☐ Adjustable armature re-centering for horizontal and vertical operation or other external pre-loads
- ☐ Rugged standard armature and linear guidance system carries full weight of body
- ☐ One-Man Portability — less than 80-lb total weight
- ☐ Optional Air Bearings and Lightweight Armature

APS

All. N°6

APS 113 with
0052 Auxiliary Table

0072 Cradle CULLA



DESCRIPTION AND CHARACTERISTICS

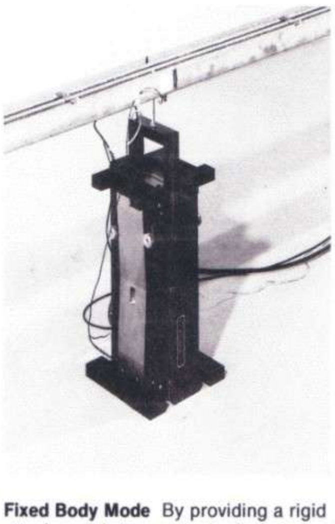
The APS 113 **ELECTRO-SEIS**® has been optimized for driving structures at their natural resonance frequencies. It is an electrodynamic force generator, the output of which is directly proportional to the instantaneous value of the current applied to it, independent of frequency and load response. It can deliver random or transient as well as sinusoidal waveforms of force to the load. The armature has been designed for minimum mass loading of the drive point. The ample armature stroke allows driving antinodes of large structures at low frequencies and permits rated force at low frequencies when operating in a free body mode.

The unit employs permanent magnets and is configured such that the armature coil remains in a uniform magnetic field over the entire stroke range — assuring force linearity. The enclosed, self-cooled construction provides safety and minimum maintenance. Attachment of the armature to the drive point is accomplished by a simple thrust rod provided by the user.

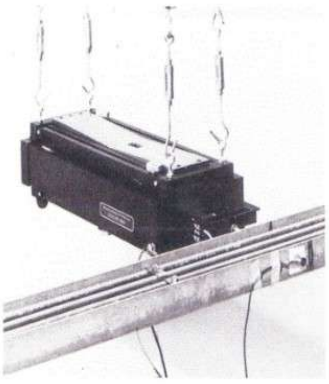
A low frequency amplifier, such as the APS 114 or APS 124 **DUAL-MODE**™ Power Amplifier, is required to provide armature drive power.

MODES OF OPERATION

Free Armature Mode In this mode, the armature provides the reaction mass for force delivered to the test structure via the shaker body. Auxiliary reaction mass may be added to the armature to decrease the low frequency limit for rated force operation. The APS 113 and 0112 Reaction Mass may be used in a vertical or horizontal free armature mode with rated force down to 2 Hz. Feet and carrying handles are provided for ease in placement of the shaker on horizontal test surfaces.



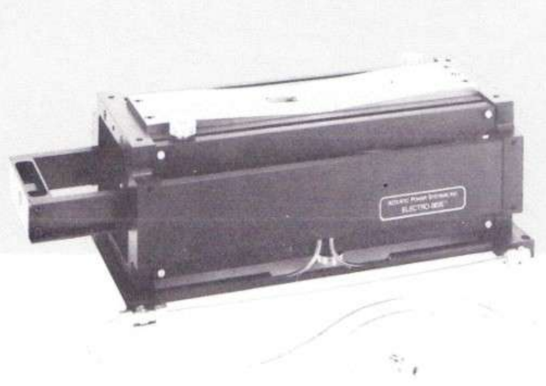
Fixed Body Mode By providing a rigid attachment between the body and ground, the full relative velocity and stroke capability is available for load motion. Maximum rated force can be delivered down to 0.01 Hz and 70% maximum to 0 Hz.



Free Body Mode In this mode, the body provides the reaction mass. Load and body motion are accomodated within the total relative velocity and stroke. Because of the high cross-axis stiffness provided by the armature linear guidance system, the shaker may be supported above ground level by means by suspension lines attached to the body — or the shaker may be supported from the beneath by the APS 0072 Cradle Assembly which supports the armature directly and the body via the guidance system. This provides a convenient mounting for introducing force parallel to a horizontal mounting surface. Examples of such surfaces include floors, roofs, platforms, cabinets, bridges and tanks.

Shaker Table Mode Auxiliary tables are available which attach directly to the armature and enable the basic shaker to provide long stroke, low frequency excitation to components or model structures mounted on the tables. APS 0052 Auxiliary Table provides a 9 in x 12 in horizontal load mounting surface for horizontal motion rated for 50 lb test loads. The APS 0077 Auxiliary Table provides the same load mounting surface for vertical motion.

APS 113 with 0112 Reaction Mass



APS 113 Air Bearing Shaker

OPTIONAL CONFIGURATIONS

APS 113-AB Air Bearing Model Air lubricated bushings replace the linear ball bushings used in the basic **ELECTRO-SEIS** armature guidance system. In addition an air distribution system, tie down and leveling base are provided.

The near zero friction of the air bushings is an essential feature for measuring resonance decay rates in very lightly damped structures.

The Air Bearing configuration extends the application of the basic APS 113 to include the calibration and evaluation of accelerometers and other motion transducers in the seismic frequency range.

APS 113-LZ Low Impedance Coil
All features of the basic **ELECTRO-SEIS** Shaker are retained. The drive coil is wound in a manner which allow series or parallel connection, offering the user the choice of standard or low impedance. This option is required if the shaker is to be used with the APS 124 **DUAL-MODE** Power Amplifier for extended frequency range or random noise excitation.

APS 113-HF High Force Coil
All features of the basic **ELECTRO-SEIS** Shaker are retained as in the APS 113-LZ. The drive coil is provided to match the APS 124 **DUAL-MODE** Power Amplifier for 40% increase in force with a 50% duty cycle (1/2 hr cycle).

APS 113-LA Lightweight Armature
The body of the **ELECTRO-SEIS** Shaker is retained but the armature and guidance system are replaced with elements offering substantial weight reduction. The drive coil is lightened — with corresponding reduction in maximum force — and the armature guidance system elements are reduced in size and weight. This results in a corresponding reduction in cross axis stiffness and load carrying ability. The long stroke capability is retained and the frequency range for maximum force output is extended to 1000 Hz.

The Lightweight Armature is a desirable feature when using the shaker for exciting structures having low modal mass.

SPECIFICATIONS	Model 113	Model 113-AB	Model 113-LA	Model 113-LZ	Model 113-HF
Maximum Force, Vector	30 lb (133N)	30 lb (133N)	10 lb (45N)	30 lb (133N)	42 lb (186N)*
Maximum Velocity, Vector	30 in/s (76 cm/s)	30 in/s (76 cm/s)	30 in/s (76 cm/s)	30 in/s (76 cm/s)	30 in/s (76 cm/s)
Maximum Stroke, p-p	6.25 in (15.9 cm)	6.25 in (15.9 cm)	6.25 in (15.9 cm)	6.25 in (15.9 cm)	6.25 in (15.9 cm)
Armature Weight	4.9 lb (2.2 kg)	5.1 lb (2.3 kg)	.67 lb (.30 kg)	5.0 lb (2.27 kg)	4.9 lb (2.20 kg)
Maximum Overhung Load at Armature Attachment Point	20 lb (9 kg)	2 lb (.9 kg)	2 lb (.9 kg)	20 lb (9 kg)	20 lb (9 kg)
Air Pressure Required	N/A	30 PSIG (2kg/cm²)	N/A	N/A	N/A
Armature Coil Impedance	8 Ohm	8 Ohm	4 Ohm	8 Ohm/2 Ohm	4 Ohm
Total Shaker Weight	80 lb (36 kg)	80 lb (36 kg)	75 lb (34 kg)	80 lb (36 kg)	80 lb (36 kg)
Shipping Weight	100 lb (45 kg)	100 lb (45 kg)	95 lb (43 kg)	100 lb (45 kg)	100 lb (45 kg)
Overall Dimensions					
Length	20.7 in (52.6 cm)	20.7 in (52.6 cm)	20.7 in (52.6 cm)	20.7 in (52.6 cm)	20.7 in (52.6 cm)
Width	8.4 in (21.3 cm)	8.4 in (21.3 cm)	8.4 in (21.3 cm)	8.4 in (21.3 cm)	8.4 in (21.3 cm)
Height	6.6 in (16.8 cm)	6.6 in (16.8 cm)	6.6 in (16.8 cm)	6.6 in (16.8 cm)	6.6 in (16.8 cm)
Matching Power Amplifier	APS 114	APS 114	APS 114	APS 124	APS 124

*50% Duty Cycle

APS **ACOUSTIC POWER SYSTEMS, INC.**
Systems for Generating Controlled Vibration

PERFORMANCE

The primary purpose of the APS 113 **ELECTRO-SEIS®** is to determine the dynamic characteristics of mechanical structures. At resonance, a large amount of energy is contained in the structure, and the shaker must accomodate the resulting motion. However, it need be only supply the real mechanical power dissipated by damping mechanisms within the structure.

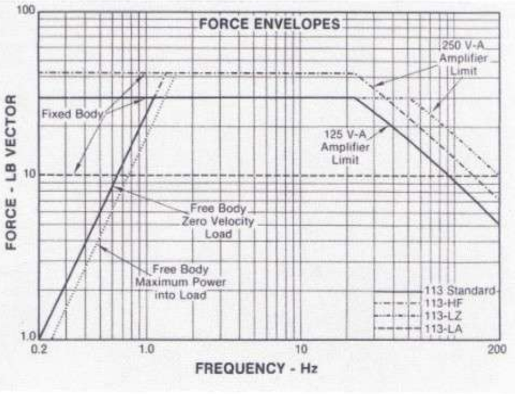
If a drive point on a structure in resonance is vibrating with a velocity of 30 in/s and a force of 30 lb is required to sustain the vibration level, then the shaker will be delivering approximately 50 watts to the structure. Such a load on the shaker is termed a matched resonant load, and it is purely resistive since the force is in a phase with the velocity.

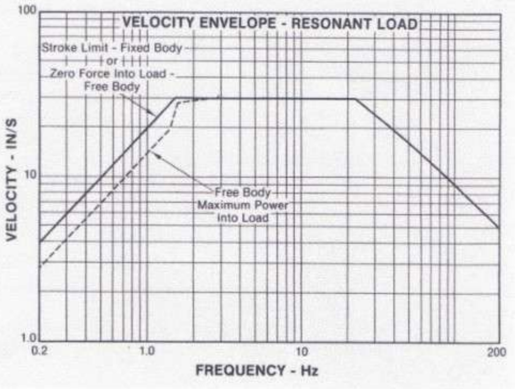
If the resonant load input is other than 30 lb ÷ 30 in/s, the full 50 watts of mechanical power cannot be delivered to the structure, the system being either force or velocity limited. If the resulting maximum response level is not great enough, the user may have the option of moving the shaker to a drive point having an impedance closer to the matched value, or adding more shakers to the array driving the structure.

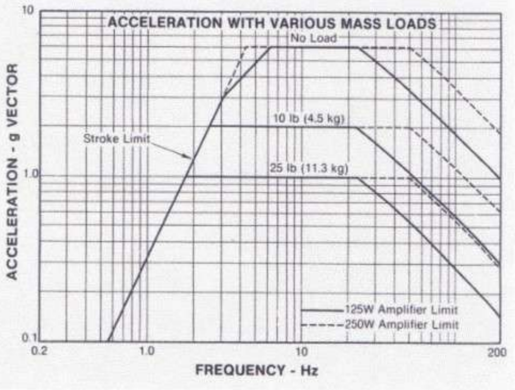
Within the limitations of maximum force and velocity, the actual power delivered to a structure is a function of the input mechanical impedance at the drive point. In typical modal testing, this input impedance varies widely in magnitude and phase angle. At different frequencies, the input impedance of the drive point may appear predominately spring-like, mass-like, or resistive. Since the object of the tests is to establish resonant modes, at which the input mechanical impedance of all drive points are resistive, the shaker's maximum performance capability is most meaningful stated in terms of the force and velocity that can be obtained when driving a matched resistive load.

Therefore performance is given in the form of graphs which present the envelopes of maximum force and velocity delivered to a resonant structure as functions of the resonance frequency of the structure.

Acceleration performance of the APS 113 **ELECTRO-SEIS** with various mass loads is shown in the lower graph for the 30-lb rating.







SYSTEM EQUIPMENT

Model 114 DUAL-MODE™ Power Amplifier (125 V-A)
Model 124 DUAL-MODE™ Power Amplifier (250 V-A)
Model 115 Control Panel
Model 123 Rack Enclosure
Interconnect Cable 0081-20A/2C

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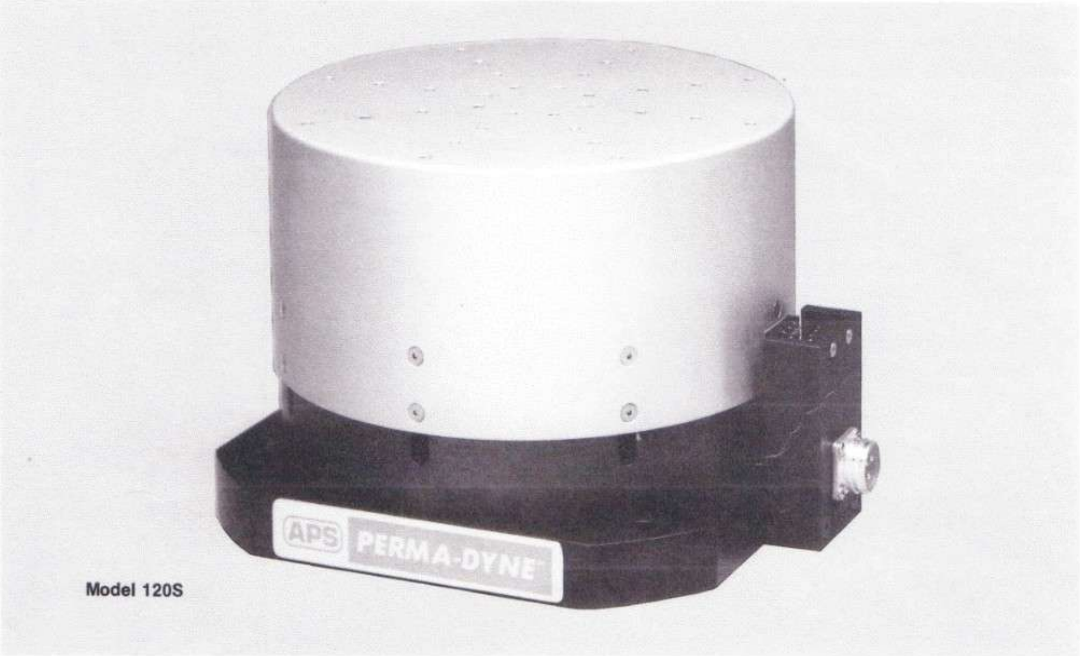
LARGE TABLE SHAKER

70-lb, 310-N force
9-in, 230-mm table



Model 120S

PERMA-DYNE™

The APS 120S ***PERMA-DYNE*** Shaker is a small, permanent magnet, electrodynamic shaker designed for vibrating relatively heavy loads. The large table and high load carrying ability permit direct mounting of many test articles without the need for heavy fixtures and external supports. The shaker is particularly suited for applications calling for a large load mounting surface.

APPLICATIONS

- Vibration testing and stress screening of circuit boards, mechanical devices and multiple small components
- Calibration of vibration transducers
- Excitation of structures for modal analysis

FEATURES

☐ 70-lb, 310-N vector force

☐ 9-in, 230-mm load mounting table diameter

☐ Rugged armature guidance system – carries 25-lb, 11-kg test load

☐ Efficient self-cooling – requires no blowers or air hoses

☐ Compact design – complete magnetic structure contained within the table diameter

APS

All. N°7

APS Dynamics, Inc.

Systems for Generating Controlled Vibration

DESCRIPTION

The Model 120S ***PERMA-DYNE*** Shaker is an electrodynamic shaker capable of producing random or transient as well as sinusoidal acceleration waveforms. Force generated by the shaker is proportional to the instantaneous current supplied by the power amplifier.

The unit uses a symmetrical permanent magnet circuit for maximum force/current linearity. Cooling of the large diameter armature coil is accomplished through conduction to the large area outside ring of the armature. The enclosed design provides safety and minimum maintenance.

The armature table is suspended and guided by a pair of widely separated, high stiffness rubber flexures.

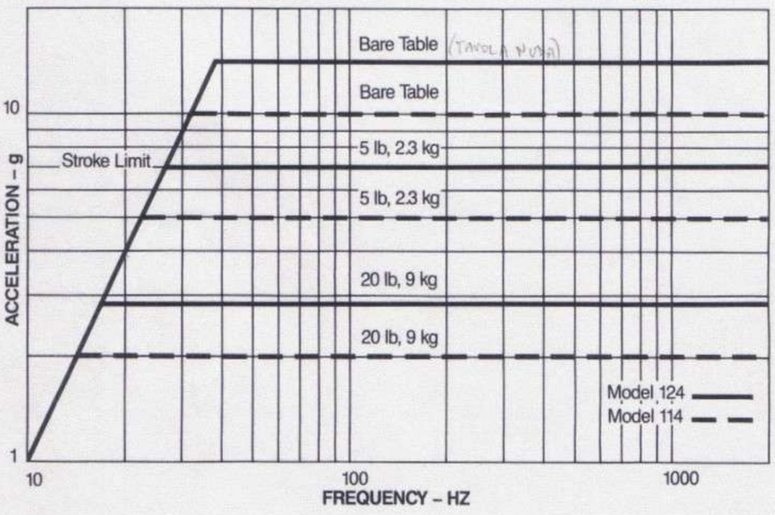
PERFORMANCE

Performance envelopes showing acceleration levels versus frequency for various mass loads are shown on the graph.

SPECIFICATIONS

Maximum Force, vector	70 lb, 310 N
Maximum Stroke, p-p	0.2 in, 5.1 mm
Flexure Stiffness	500 lb/in, 9.0 kg/mm
Maximum Load Weight	25 lb, 11 kg
Frequency Range	0 – 2000 Hz
Armature Weight	5 lb, 2.3 kg
Load Mounting Attachment Points	28
Thread Size	10-32 UNF Inserts M-5 Optional
Outline Dimensions	
Base	9.16 × 9.16 in. 233 × 233 mm
Height	6.6 in, 168 mm
Shaker Weight	55 lb, 25 kg
Matching Power Amplifiers	
Sine Wave, 50 lb	APS Model 114
Sine Wave, 70 lb	APS Model 124
Random	APS Model 124-EP

MAXIMUM ACCELERATION LEVELS FOR VARIOUS TEST LOADS



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