

# FISICA MUSICALE

**M. Sozzi –Universita' di Pisa - A.A. 2012/13**

**Raccolta di immagini per il corso**

© dei rispettivi autori

# LA CORDA VIBRANTE

# L'EQUAZIONE DELLE ONDE



Jean le Rond  
d'Alembert  
(1717-1783)

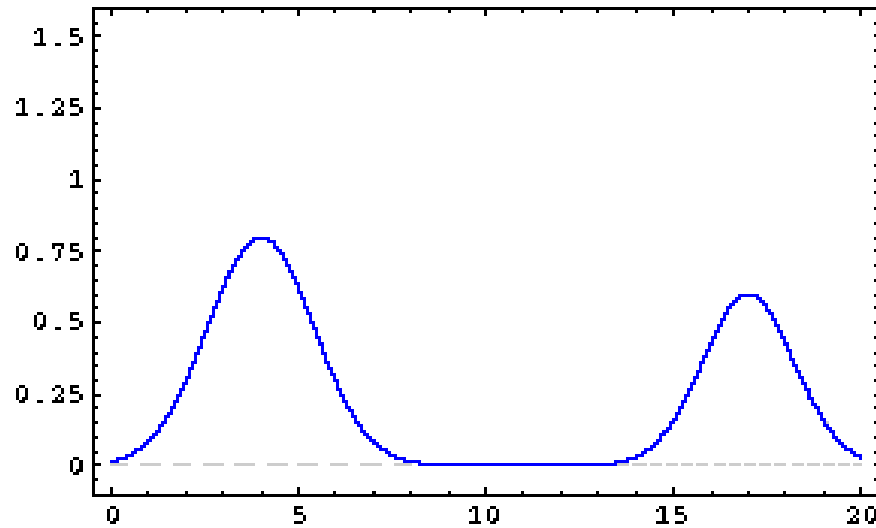
$$\frac{\partial^2 \phi}{\partial t^2} = c^2 \frac{\partial^2 \phi}{\partial x^2}$$

$$\phi = f(x - ct) + g(x + ct)$$

Per una corda:

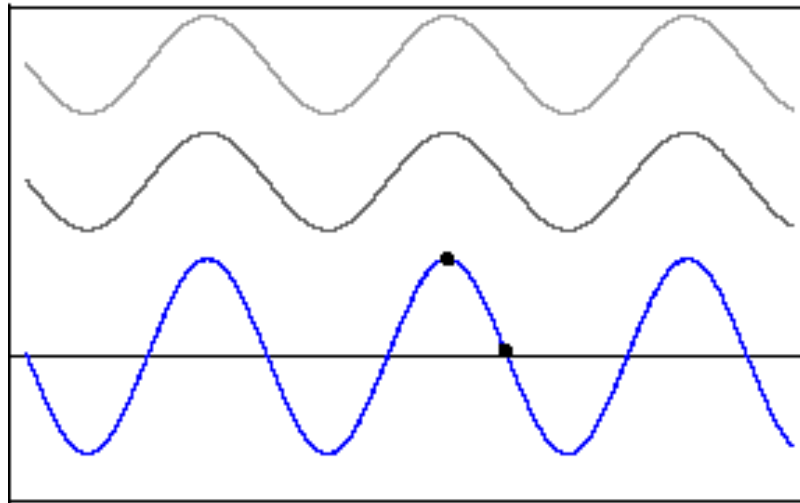
$$c = \sqrt{\frac{T}{\rho_l}}$$

# SOVRAPPOSIZIONE LINEARE (1)



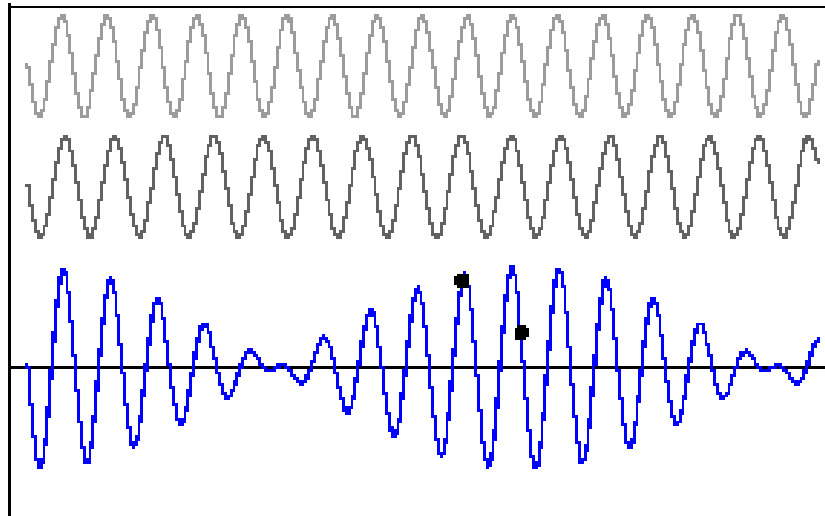
Due impulsi contro-propaganti, in assenza di dispersione.

# SOVRAPPOSIZIONE LINEARE (2)



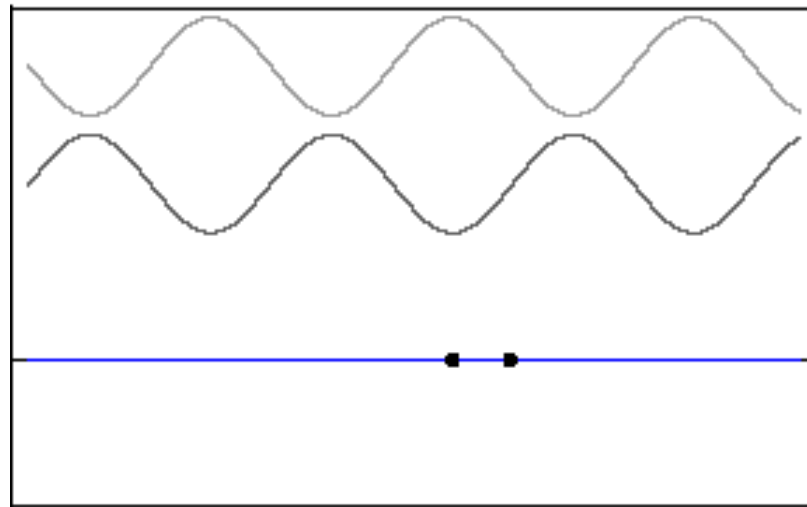
Due impulsi co-propaganti con la stessa  
lunghezza d'onda e velocità diverse:  
interferenza.

# SOVRAPPOSIZIONE LINEARE (3)



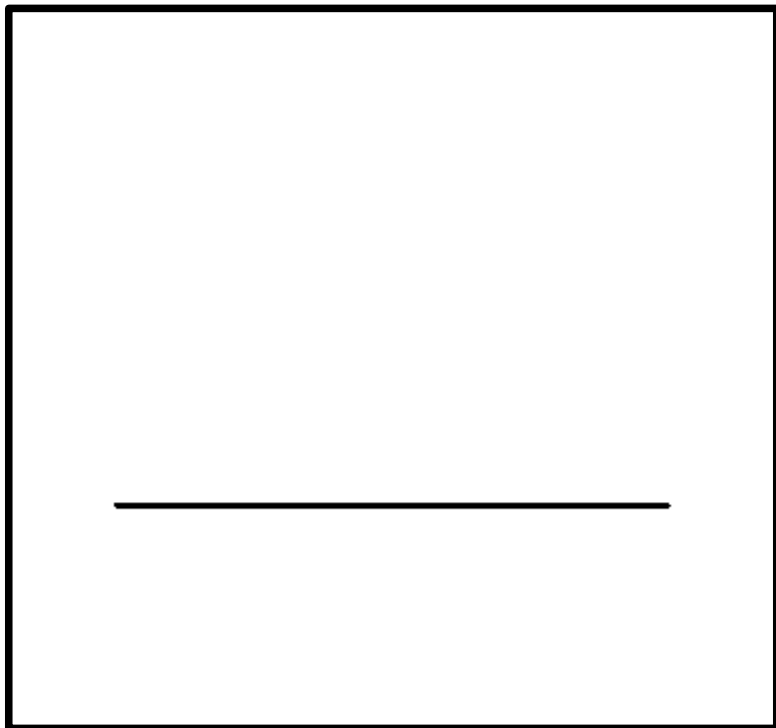
Due impulsi co-propaganti con la stessa velocità  
e lunghezze d'onda diverse: battimenti.

# SOVRAPPOSIZIONE LINEARE (4)



Due impulsi contro-propaganti di uguale frequenza:  
onda stazionaria.

# RIFLESSIONE DI ONDE



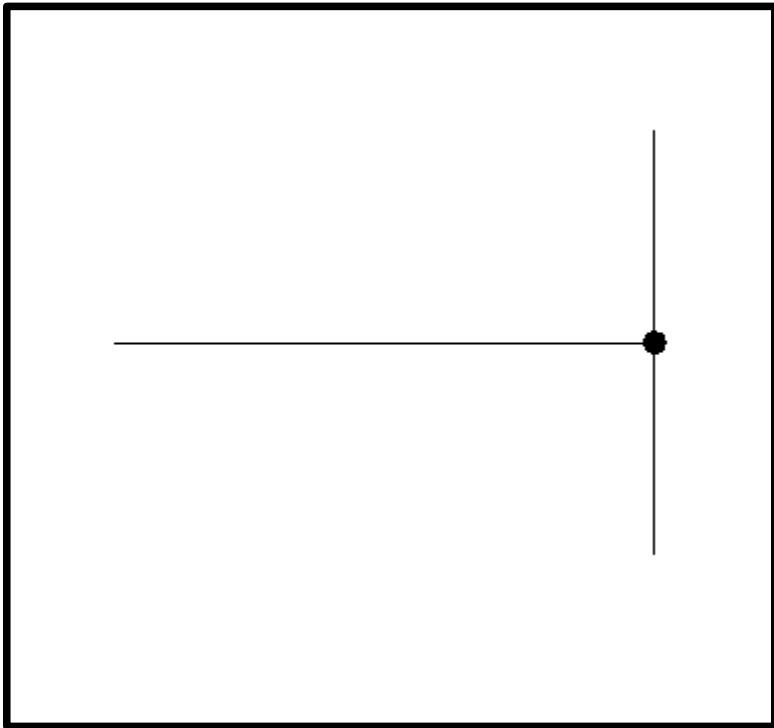
Singolo impulso in corda  
non soggetta a vincoli

Velocita' di propagazione

$$v = \sqrt{\frac{T}{\rho_l}}$$



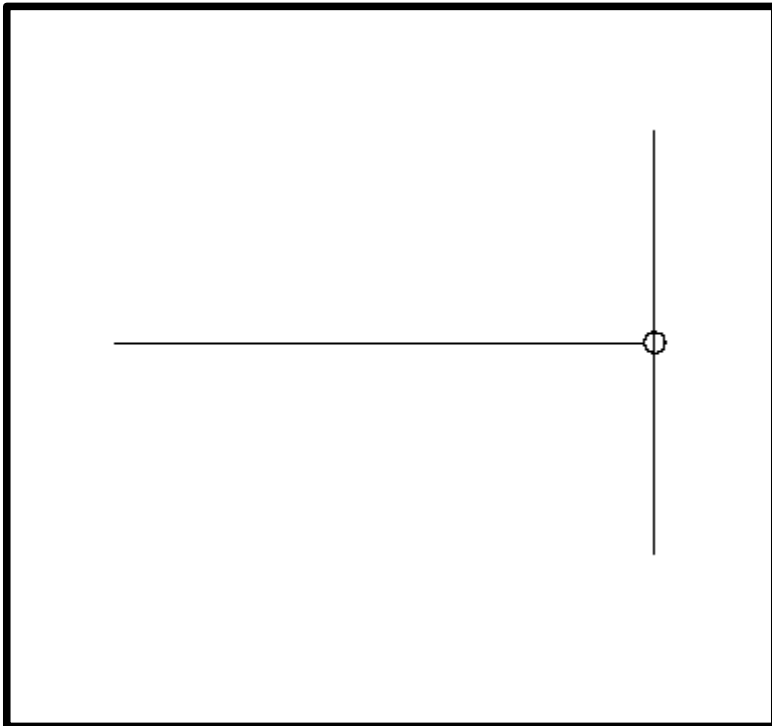
# RIFLESSIONE DI ONDE



Riflessione da estremita' fissa  
( $x$  costante, spostamento nullo)

L'impulso riflesso ha sfasamento  
di  $\pi$  radianti (inversione di fase)

# RIFLESSIONE DI ONDE



Riflessione da estremita' libera  
( $dx/dz$  costante, forza nulla)

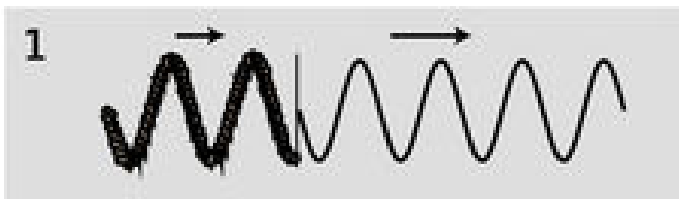
L'impulso riflesso ha sfasamento  
nullo (stessa fase)

# RIFLESSIONE DI ONDE

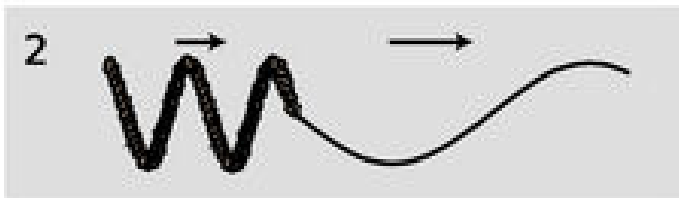
Da densita' alta (c bassa) a densita' bassa (c alta)

$$\lambda f = c_1$$

$$\lambda f = c_2$$



Variazione frequenza?  
No (discontinuita')



Variazione lunghezza d'onda  
Cuspide stazionaria?  
No (accelerazione)

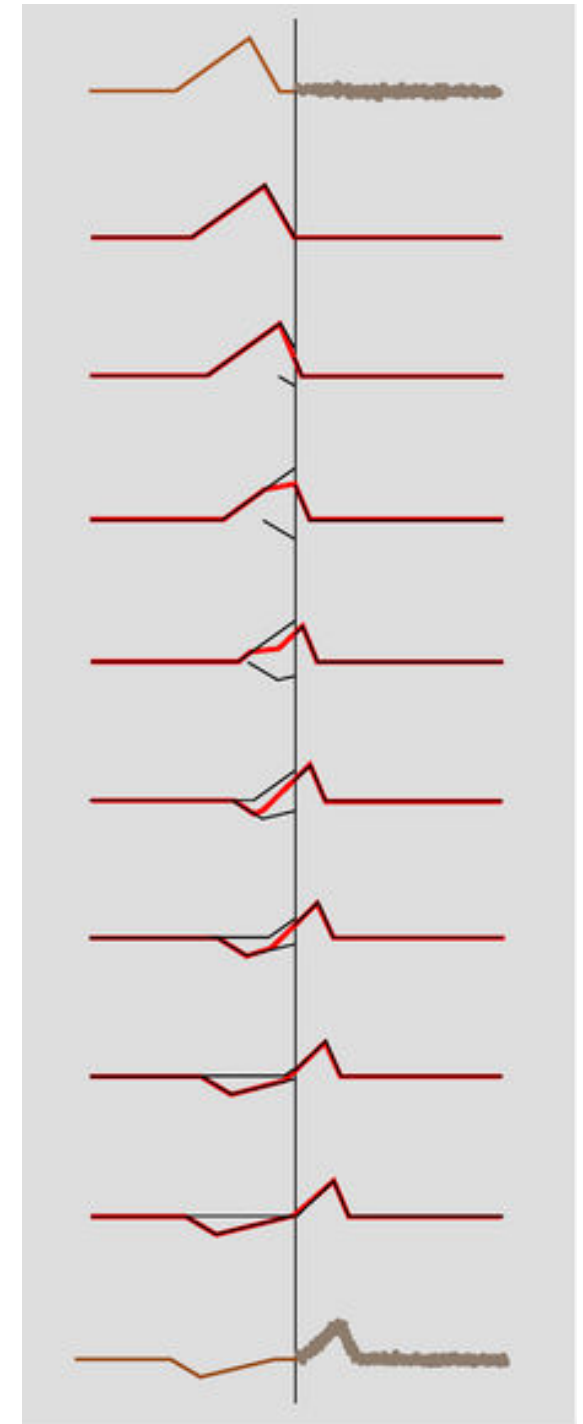
Continuita' della funzione e della sua derivata prima richiedono la presenza di onda riflessa

Continuita' funzione:

$$I+R=T$$

Continuita' derivata (senza inversione):

$$(I-R)(df/dz) = T(df/dz)(c1/c2)$$



# IMPEDENZA ACUSTICA

Rapporto tra pressione (Pa=N/m<sup>2</sup>) e velocita' (m/s)

$$Z \equiv p / \dot{x}$$

(Rayles) 1 MKS Rayl = 1 Pa s m<sup>-1</sup> = 1 kg m<sup>-2</sup> s<sup>-1</sup>

**Intensita'**  
(J m<sup>-2</sup> s<sup>-1</sup>)

$$I = p^2 / Z$$

$I_0 = 10^{-12}$  W/m<sup>2</sup>  
I(soglia del dolore) = 10 W/m<sup>2</sup>

Anche: **impedenza acustica *specifica***

Rapporto tra pressione (Pa=N/m<sup>2</sup>) e velocita' volumica (m<sup>3</sup>/s)

$$Z \equiv p / \dot{V}$$

# IMPEDENZA CARATTERISTICA

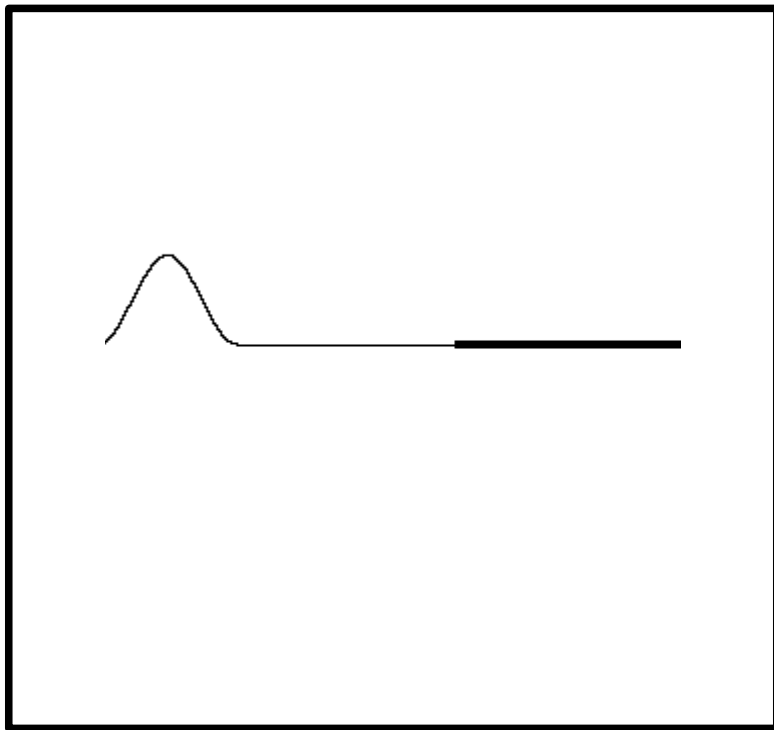
In un mezzo omogeneo:  $p = \rho c \dot{x}$

$$Z = \rho c$$

**Impedenza d'onda o  
impedenza acustica caratteristica**

Aria	415
Acqua dolce	$1.48 \times 10^6$
Acqua salata	$1.54 \times 10^6$
Gomma	$1.8 \times 10^6$
Cemento	$8 \times 10^6$
Granito	$1.6 \times 10^7$
Acciaio	$4.7 \times 10^7$
Ottone	$4.0 \times 10^7$
Alluminio	$1.7 \times 10^7$

# RIFLESSIONE DI ONDE



Da densita' bassa ( $v$  alta)  
a densita' alta ( $v$  bassa)

Riflessione da discontinuita'  
dell'impedenza (caso intermedio)

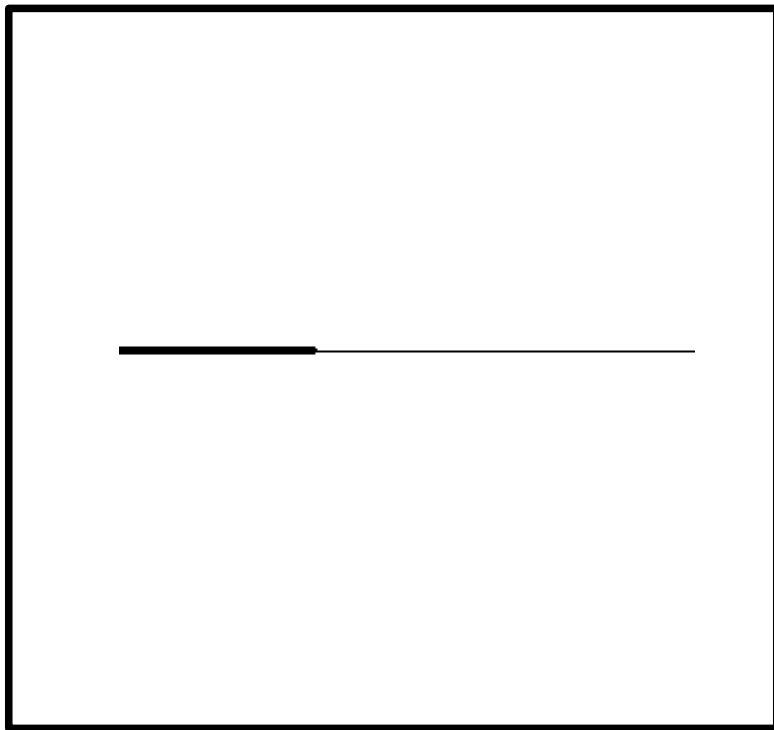
Impedenza caratteristica del mezzo:

$$Z = \rho_l c$$

Parte dell'impulso e' riflessa  
e parte e' trasmessa

$$A_1^R = \frac{Z_1 / Z_2 - 1}{Z_1 / Z_2 + 1} A_1 \quad A_2^T = \frac{2}{Z_1 / Z_2 + 1} A_1$$

# RIFLESSIONE DI ONDE



Da densita' alta (v bassa)  
a densita' bassa (v alta)

Riflessione da discontinuita'  
dell'impedenza (caso intermedio)

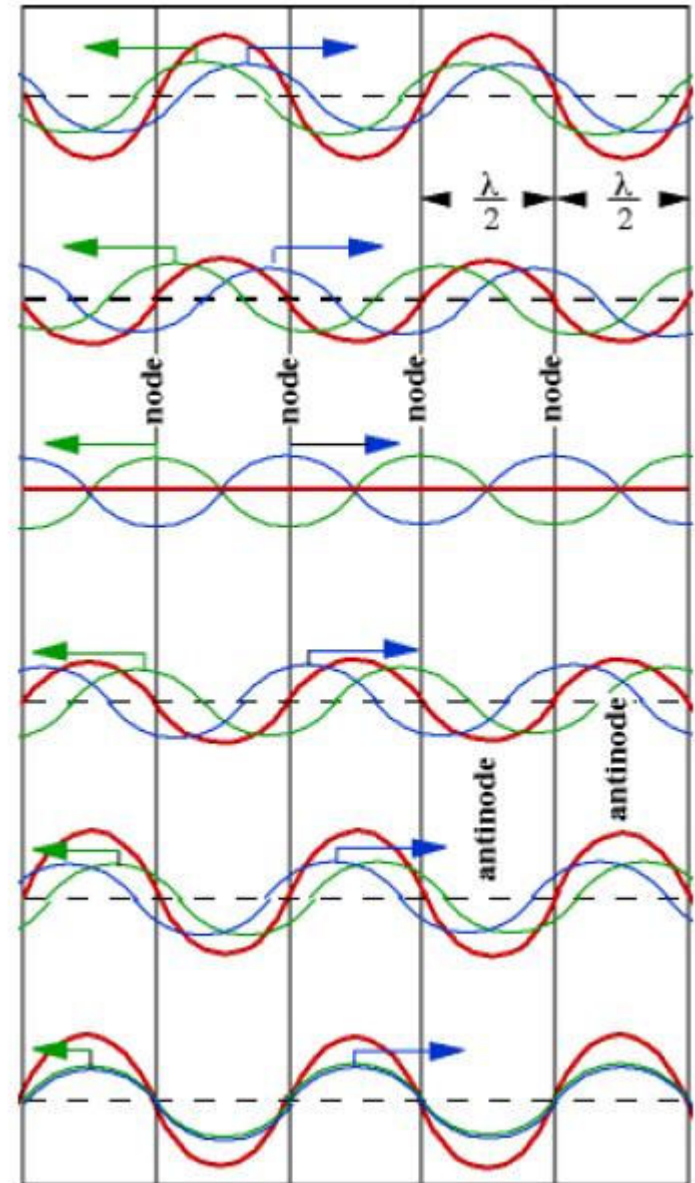
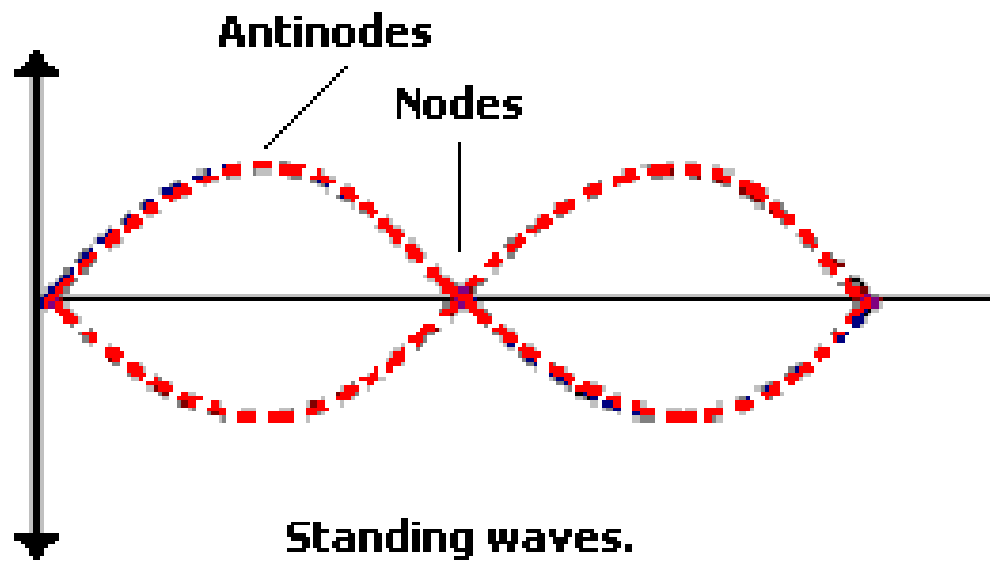
Impedenza caratteristica del mezzo:

$$Z = \rho_l c$$

Parte dell'impulso e' riflessa  
e parte e' trasmessa

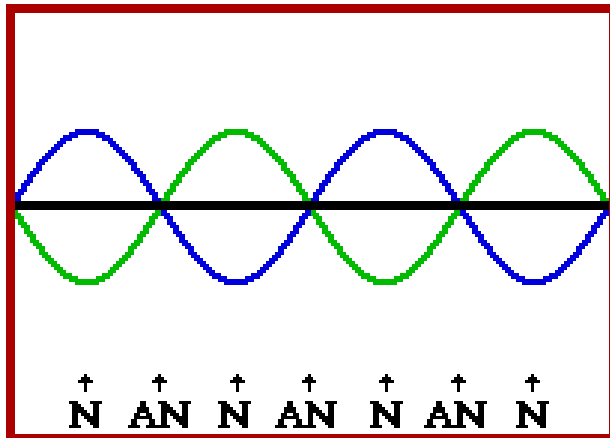
$$A_1^R = \frac{Z_1 / Z_2 - 1}{Z_1 / Z_2 + 1} A_1 \quad A_2^T = \frac{2}{Z_1 / Z_2 + 1} A_1$$

# ONDE STAZIONARIE





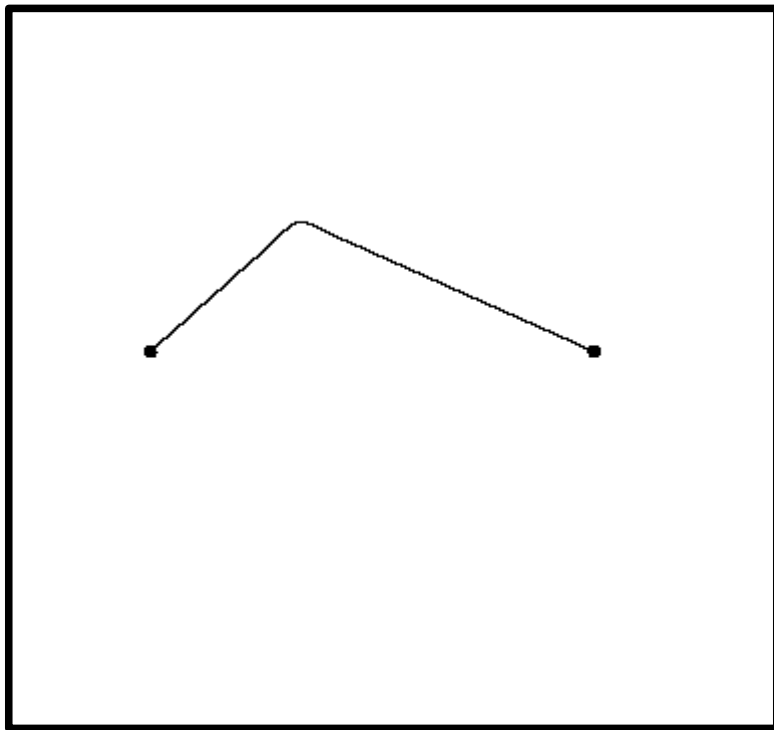
# ONDE STAZIONARIE



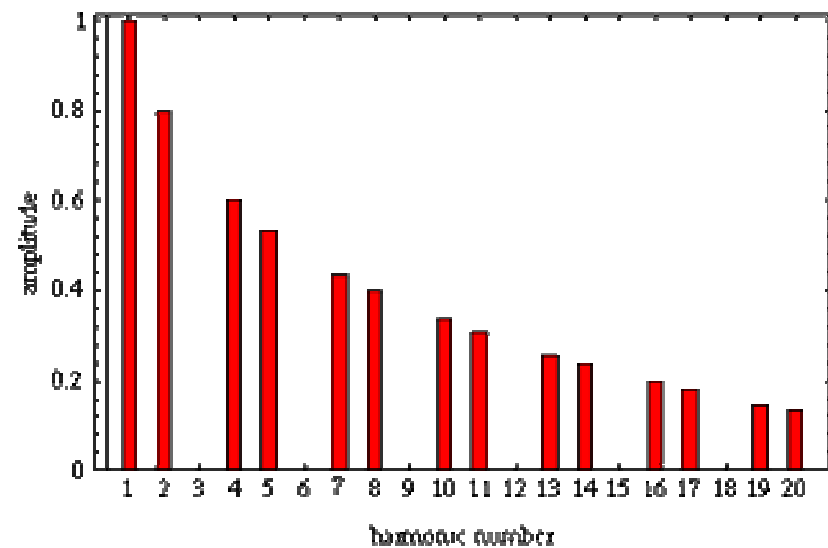
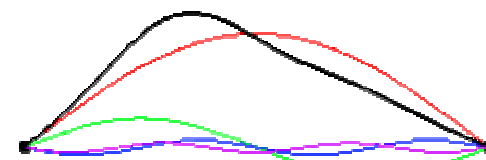
# CORDA PIZZICATA

Due onde che si propagano  
in direzioni opposte.

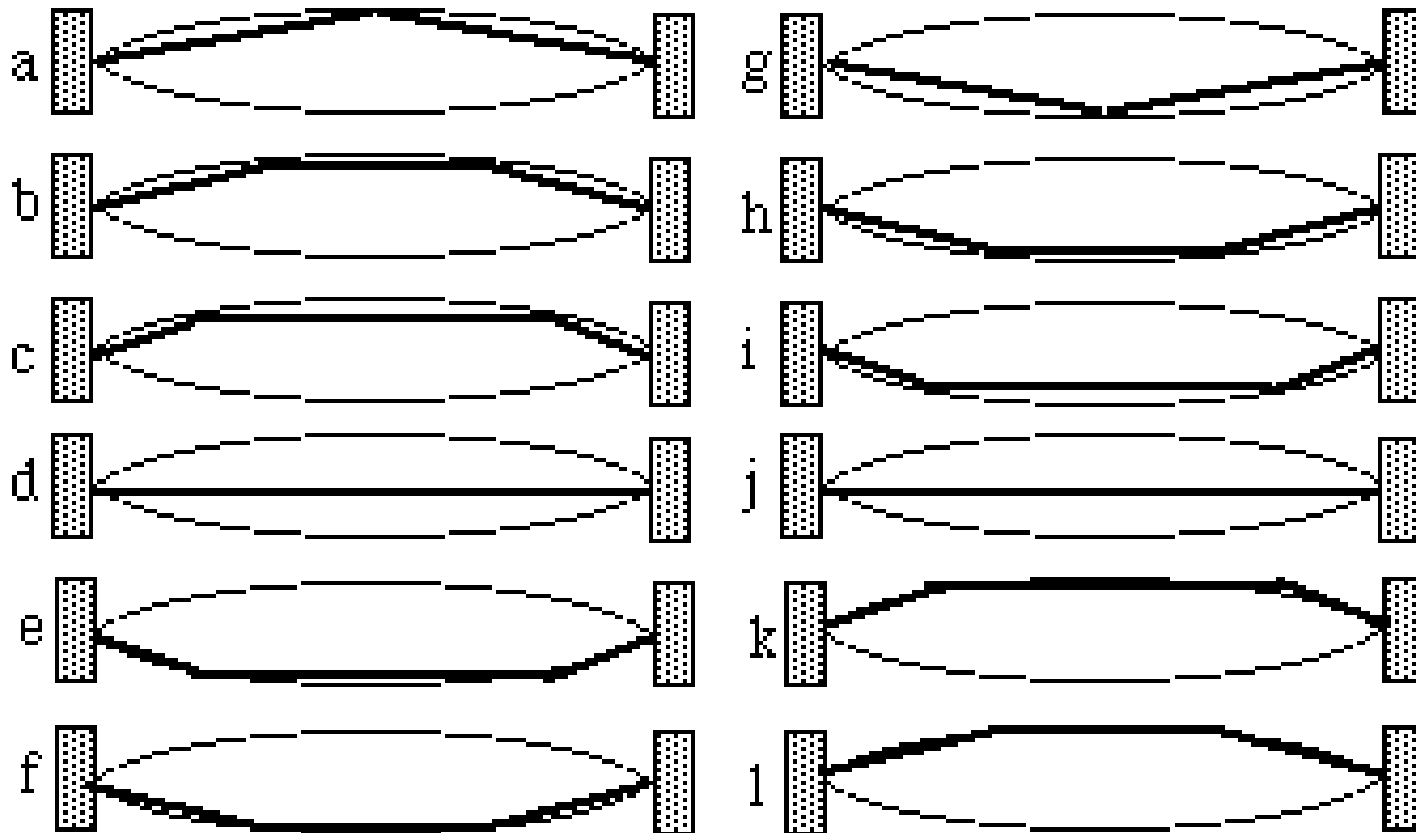
Composizione spettrale determinata  
dalle condizioni iniziali.



Pizzicata a  $x=L/3$

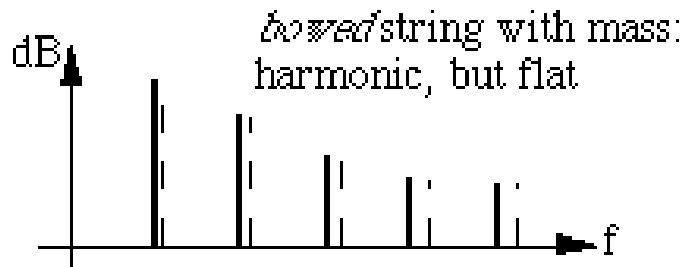
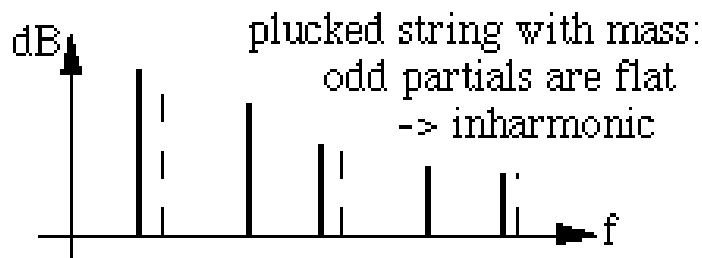
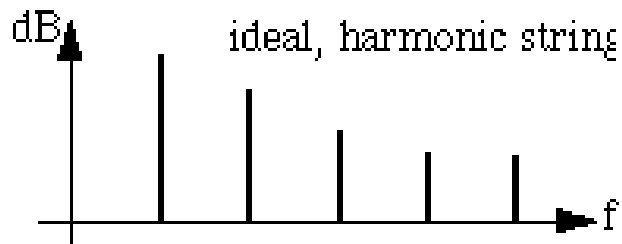


# CORDA PIZZICATA



Due vertici che si propagano in direzioni opposte.

# INARMONICITA'



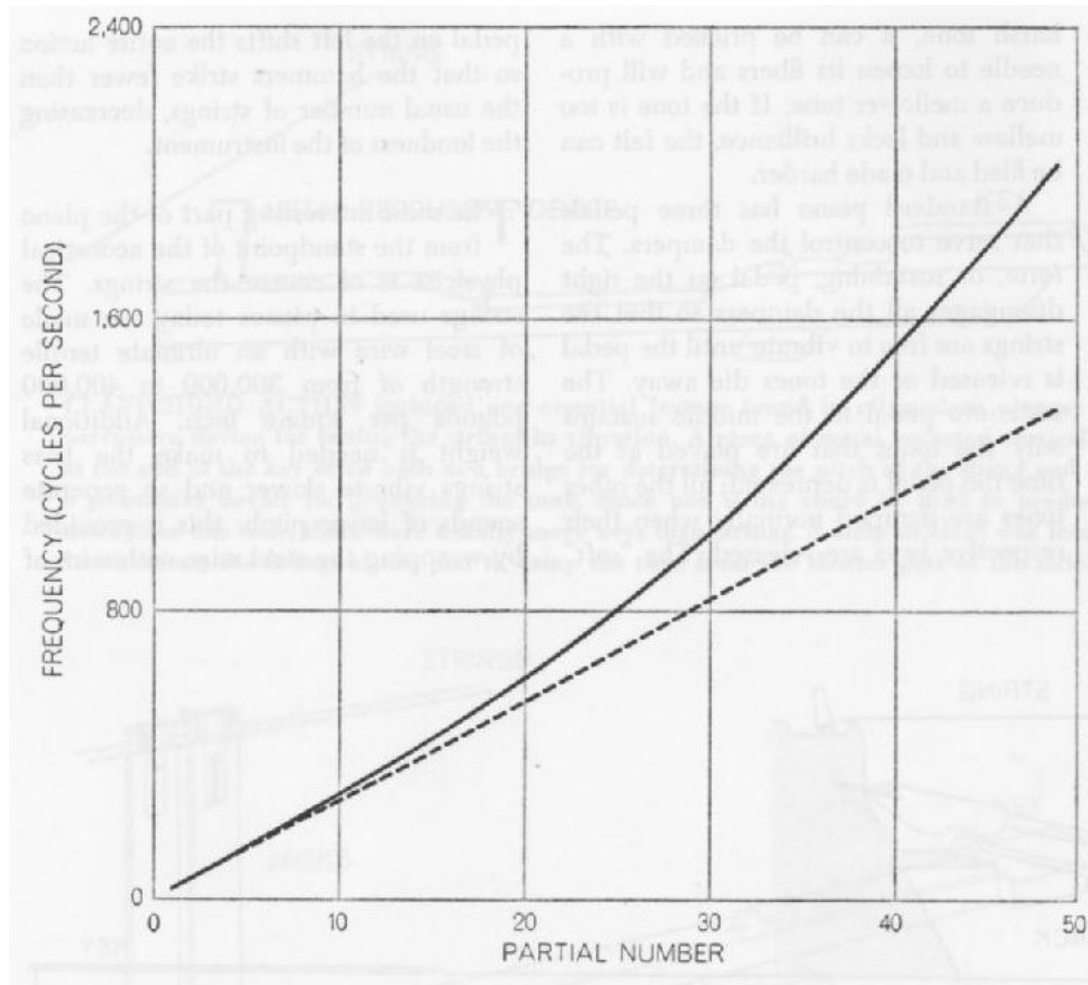
**Corda reale:** massiva, diametro finito, inelasticita' (effetto maggiore su armoniche superiori).

**Canna reale:** diametro finito, aperture

**Strumenti ad arco o a fiato:** oscillazione forzata, inarmonicita' minore (mode locking)


**Corda pizzicata o percossa:** maggiore inarmonicita'

# CORDA TESA



Inarmonicita'

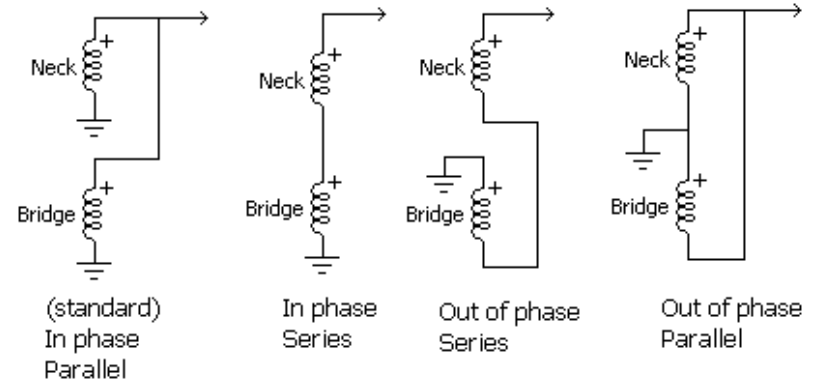
# VIBRAZIONI NEI SOLIDI

Material	Young's modulus (E) in GPa
Rubber (small strain)	0.01-0.1
Low density polyethylene	0.2
Polypropylene	1.5-2
Bacteriophage capsids	1-3
Polyethylene terephthalate	2-2.5
Polystyrene	3-3.5
Nylon	2-4
Oak wood (along grain)	11
High-strength concrete (under compression)	30
Magnesium metal (Mg)	45
Aluminium alloy	69
Glass (all types)	72
Brass and bronze	103-124
Titanium (Ti)	105-120
Carbon fiber reinforced plastic (unidirectional, along grain)	150
Wrought iron and steel	190-210
Tungsten (W)	400-410
Silicon carbide (SiC)	450
Tungsten carbide (WC)	450-650
Single Carbon nanotube [1] 	1,000+
Diamond (C)	1,050-1,200

# LA CHITARRA ELETTRICA

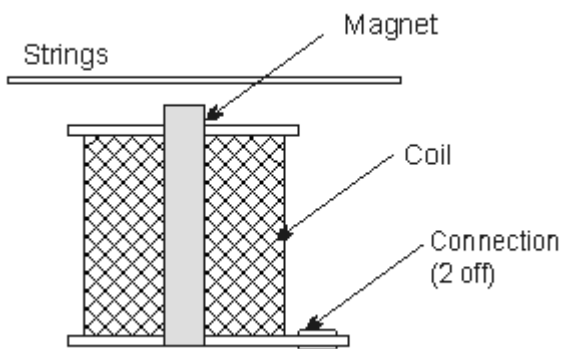


# LA CHITARRA ELETTRICA: PICKUP

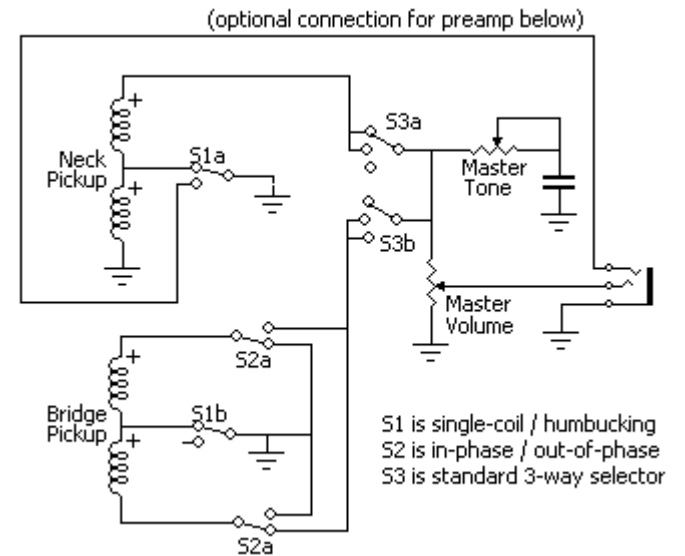
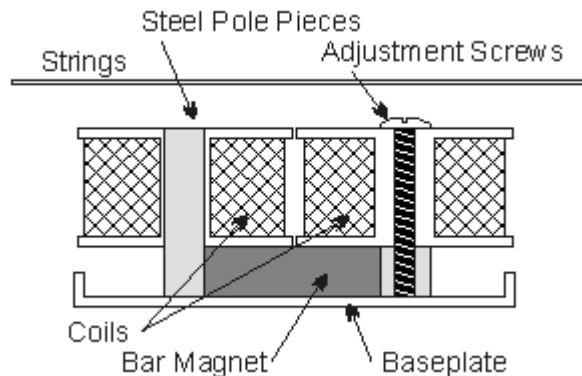


**Combinations With 2 Pickups**

## Single coil



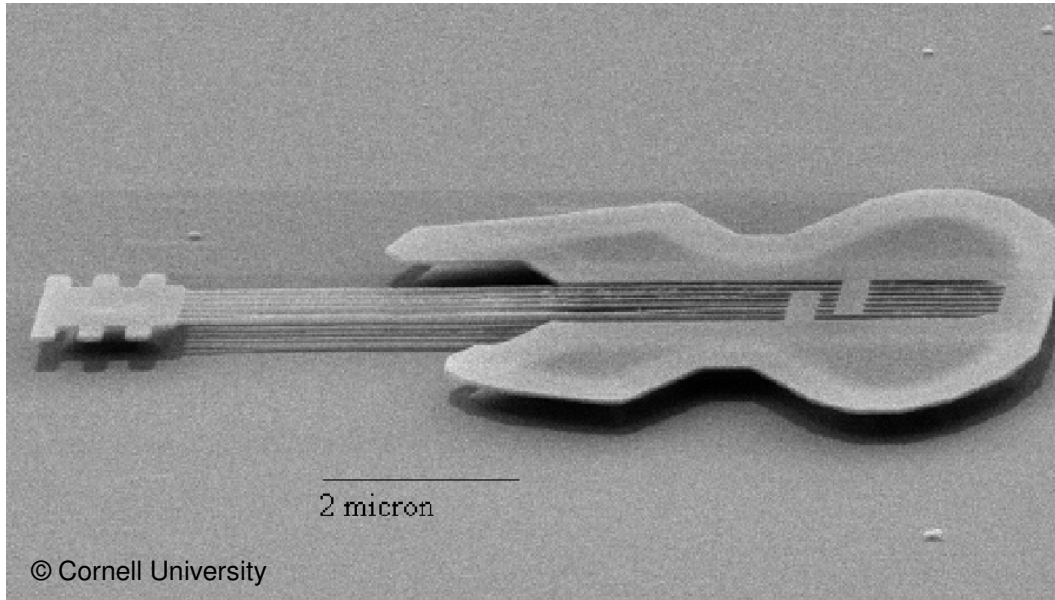
## Humbucking



S1 is single-coil / humbucking  
S2 is in-phase / out-of-phase  
S3 is standard 3-way selector



# LA NANOCHITARRA



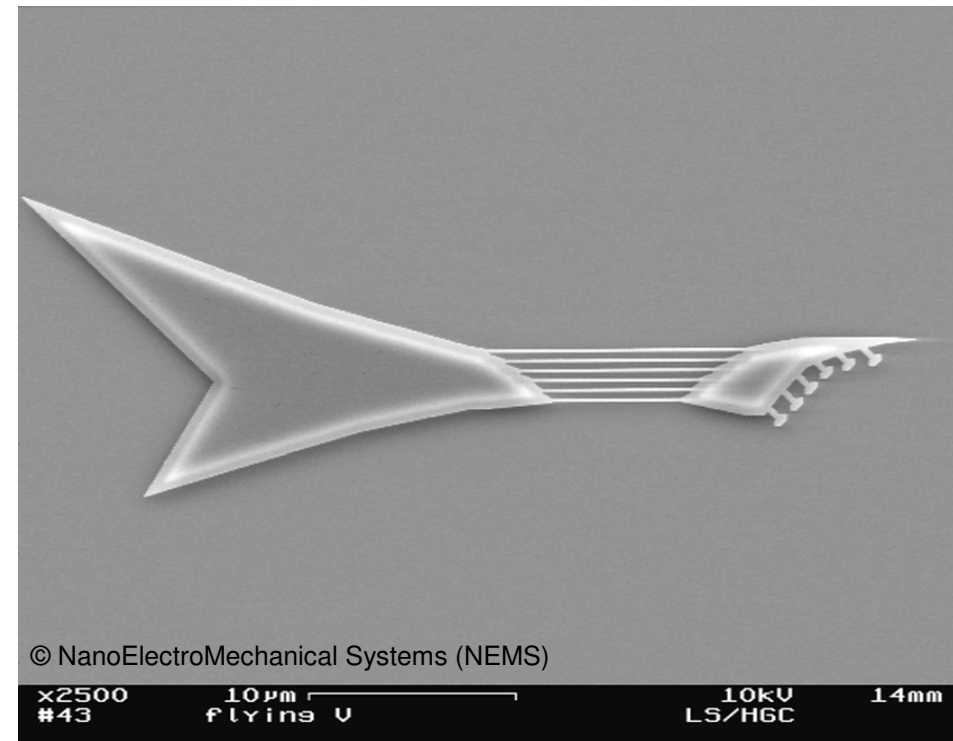
Carr, Craighead (Cornell Nanofabrication Facility)

Lunghezza 10  $\mu\text{m}$  ( $\sim$  singola cellula)

6 corde di 50 nm di diametro ( $\sim$  100 atomi)

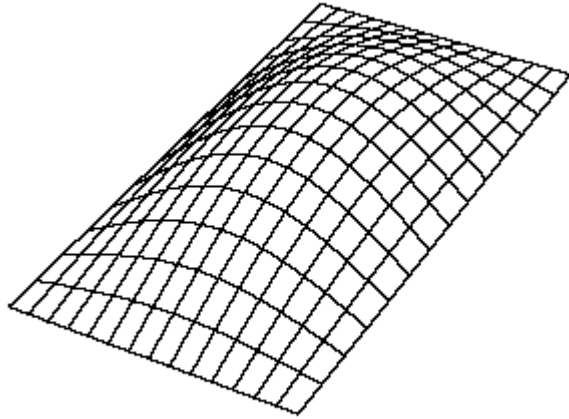
Realizzata da silicio cristallino

Sekaric, Aubin, Huang:  
corde con diametro 150-200 nm e  
lunghezza 6-12  $\mu\text{m}$ .  
Frequenza  $\times 130000$  (+17 ottave),  
determinata soltanto da lunghezza.  
Oscillazioni indotte da luce laser  
focalizzata e rivelate



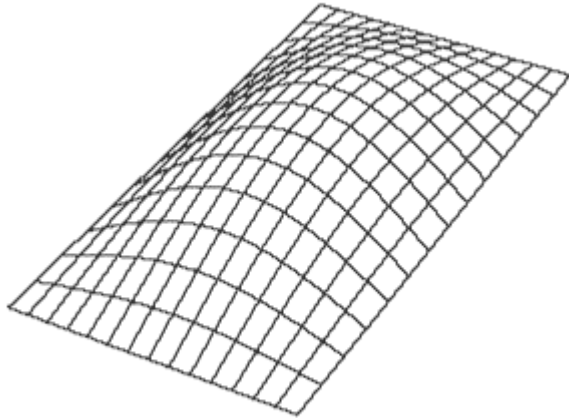
# MEMBRANE E PIASTRE

# MEMBRANE QUADRATE (1)

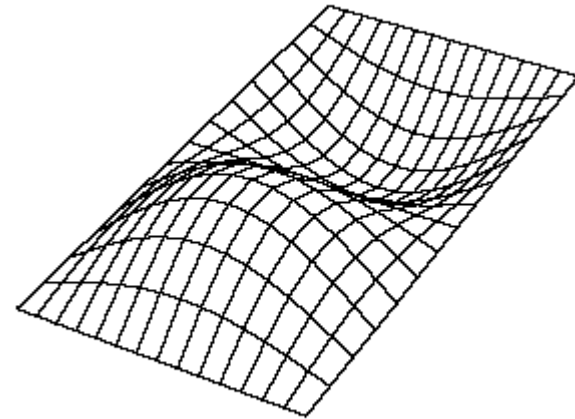


Modo (1,1)

# MEMBRANE QUADRATE (2)

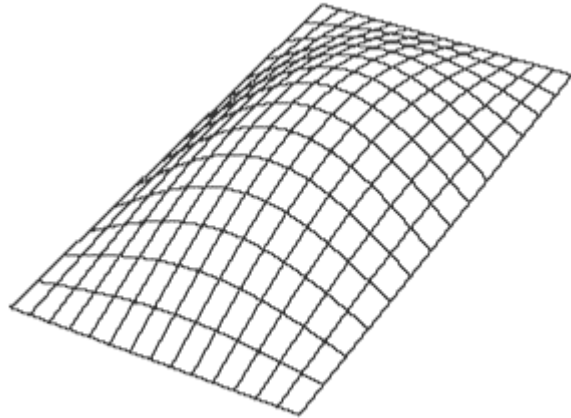


Modo (1,1)

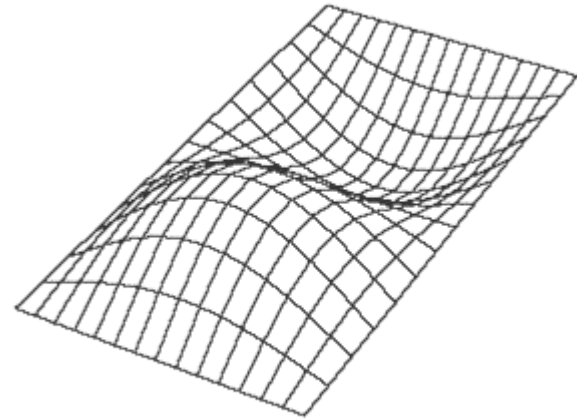


Modo (1,2)

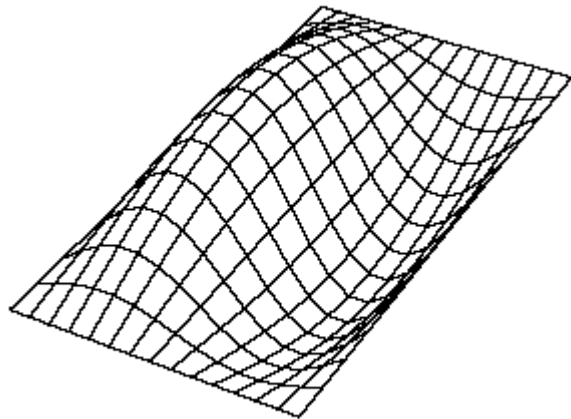
# MEMBRANE QUADRATE (3)



Modo (1,1)

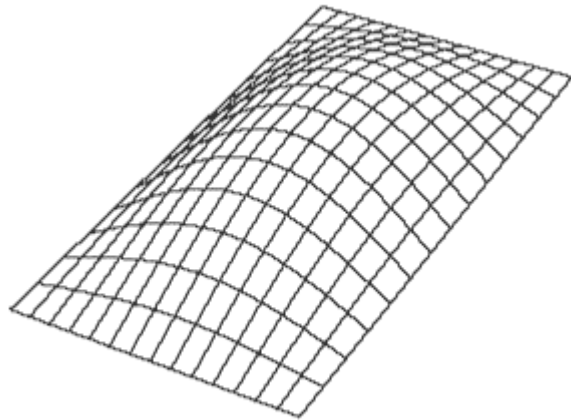


Modo (1,2)

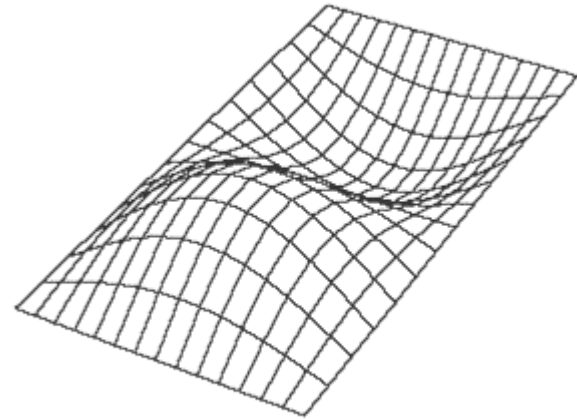


Modo (2,1)

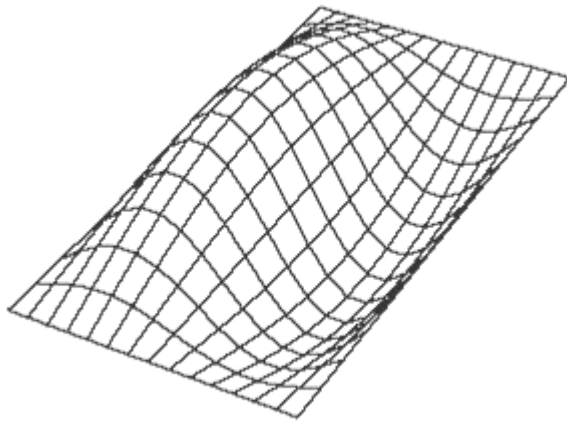
# MEMBRANE QUADRATE (4)



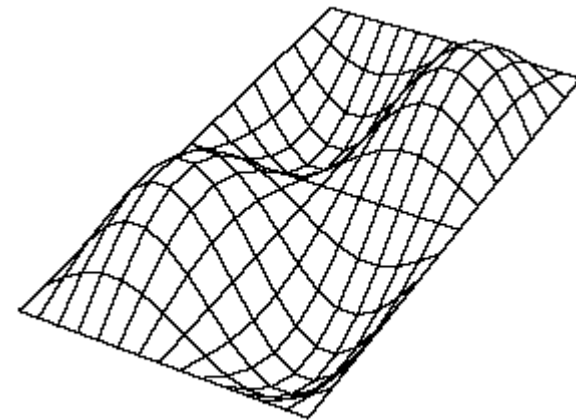
Modo (1,1)



Modo (1,2)

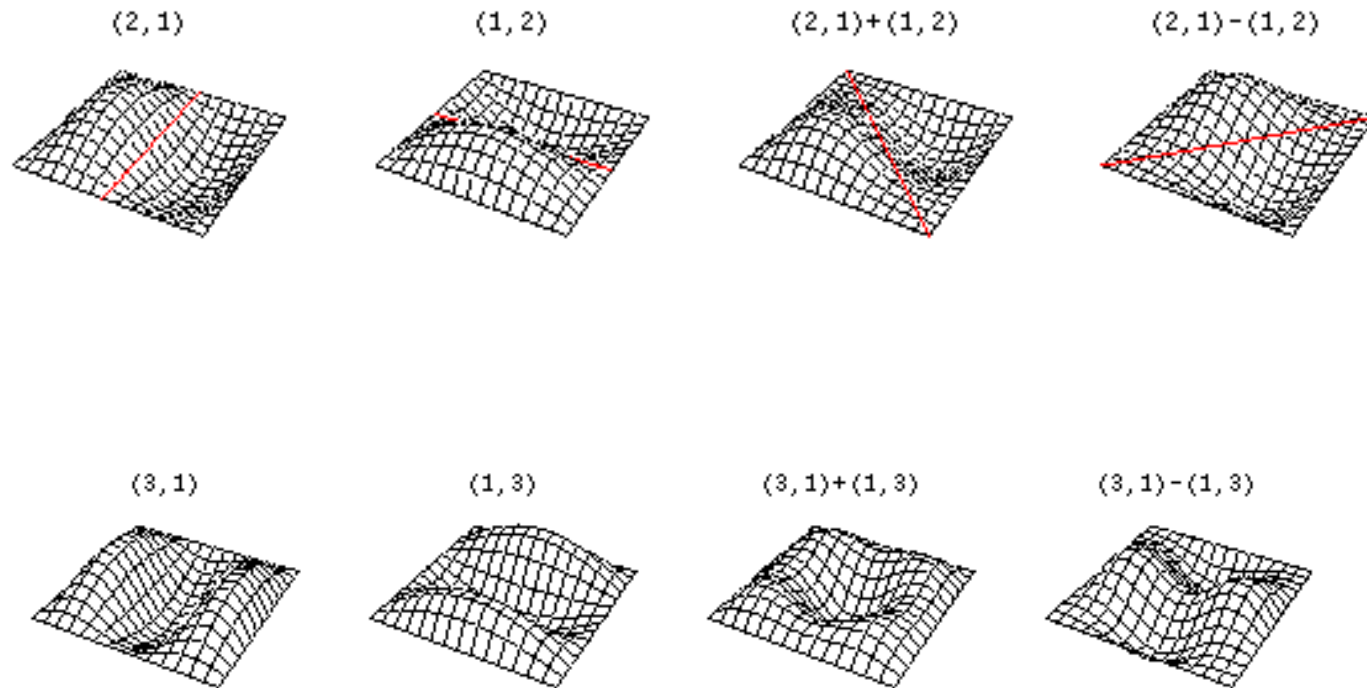


Modo (2,1)



Modo (2,2)

# MEMBRANE QUADRATE (5)

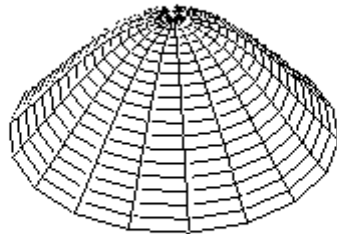


Modi degeneri

# VIBRAZIONI DI MEMBRANE (1)



$$f = 1.000$$



Modo fondamentale (0,1):  
nessuna diametro nodale ed  
un nodo circolare.

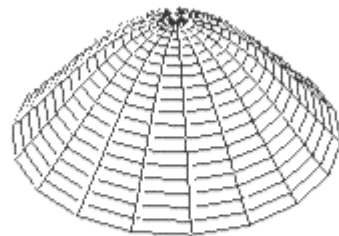
Timpano colpito al centro.  
Radiazione di monopolo: elevata  
efficienza, rapido decadimento  
(0.1 s), scarsa importanza ai fini del  
timbro



# VIBRAZIONI DI MEMBRANE (2)



$$f = 1.000$$

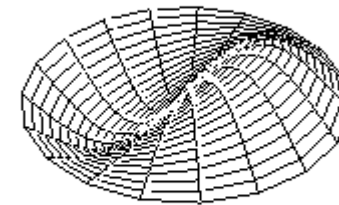


Modo fondamentale (0,1):  
nessuna diametro nodale ed  
un nodo circolare.

Timpano colpito al centro.

Radiazione di monopolo: elevata  
efficienza, rapido decadimento  
(0.1 s), scarsa importanza ai fini del  
timbro

$$f = 1.593$$



Modo (1,1): un diametro nodale  
(posizione determinata dalle  
condizioni al contorno) ed  
un nodo circolare.

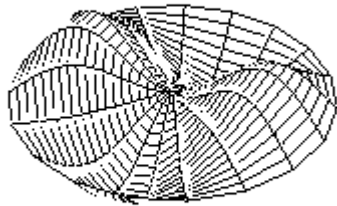
Timpano colpito da un lato.

Radiazione di dipolo: meno  
efficiente, durata alcuni secondi,  
contribuisce a determinare l'altezza.

# VIBRAZIONI DI MEMBRANE (3)



$$f = 2.135$$



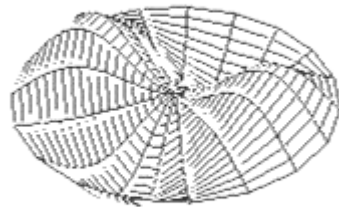
Modo (2,1):  
due diametri nodali (ortogonali) ed  
un nodo circolare.

Radiazione di quadrupolo: scarsa  
efficienza, lunga durata ed  
importanza ai fini del timbro.

# VIBRAZIONI DI MEMBRANE (4)

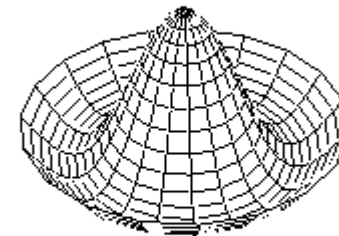


$$f = 2.135$$



Modo (2,1):  
due diametri nodali (ortogonali) ed  
un nodo circolare.  
Radiazione di quadrupolo: scarsa  
efficienza, lunga durata ed  
importanza ai fini del timbro.

$$f = 2.295$$

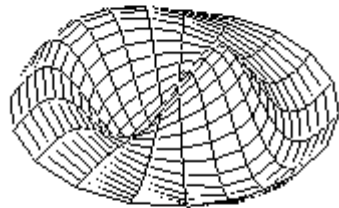


Modo (0,2):  
nessun diametro nodale e due nodi  
circolari (primo a 0.564 R)  
un nodo circolare.  
Timpano colpito al centro.  
Radiazione di monopolo e dipolo:  
scarso contributo al timbro.

# VIBRAZIONI DI MEMBRANE (5)



$$f = 2.917$$

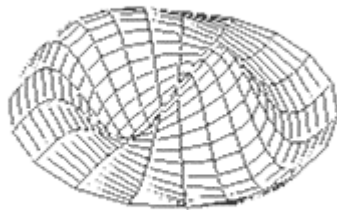


Modo (1,2):  
un diametro nodale e due  
nodi circolari.

# VIBRAZIONI DI MEMBRANE (6)

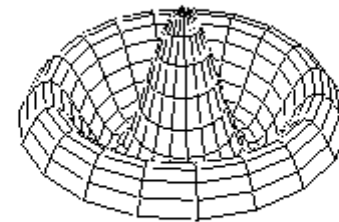


$$f = 2.917$$



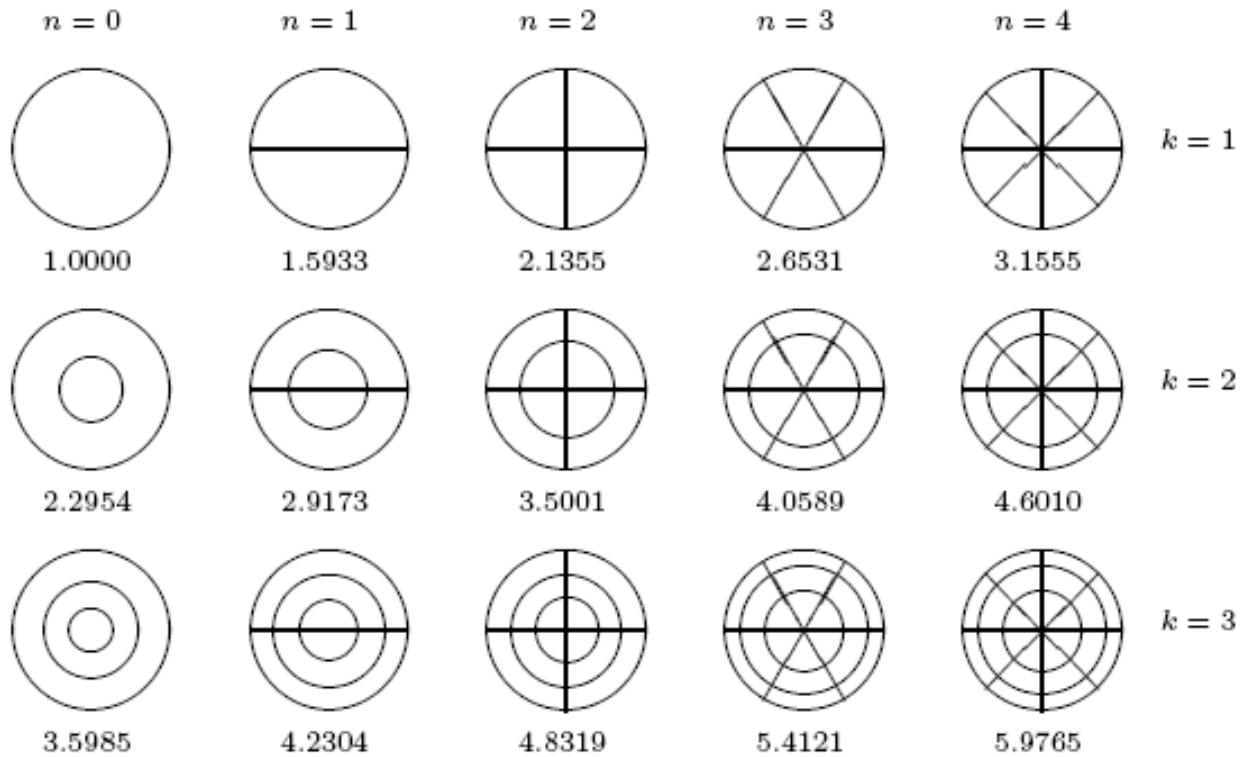
Modo (1,2):  
un diametro nodale e due  
nodi circolari.

$$f = 3.598$$

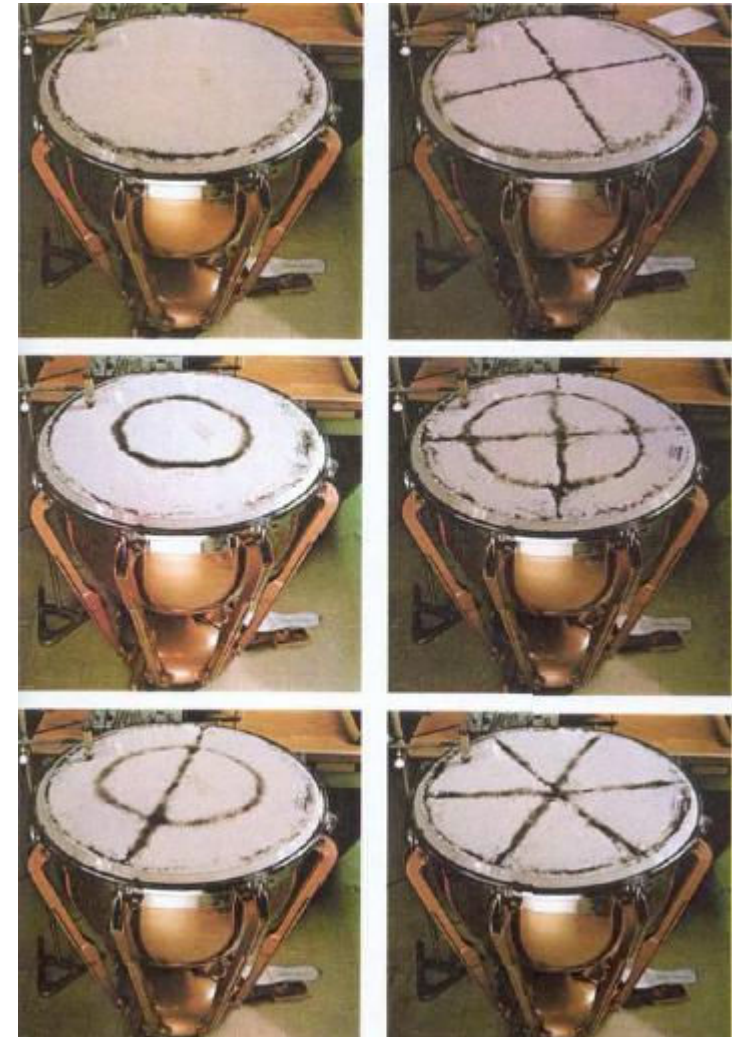


Modo (0,3):  
nessun diametro nodale e tre nodi  
circolari.

# MEMBRANE



Alcuni modi di vibrazione di una membrana circolare

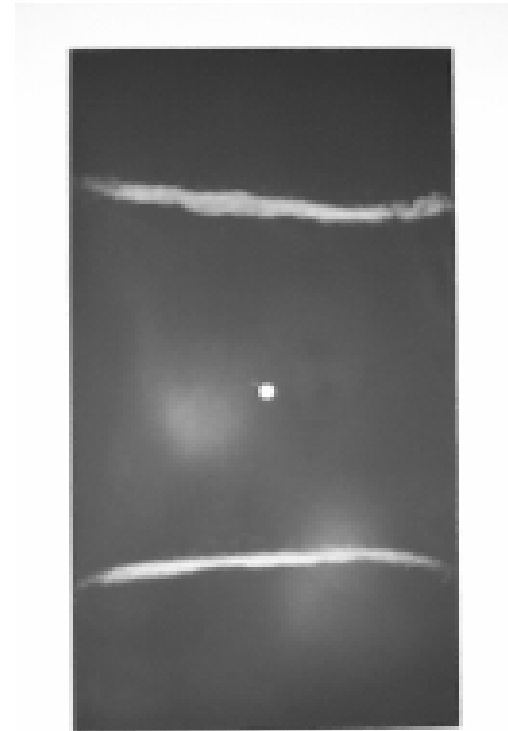
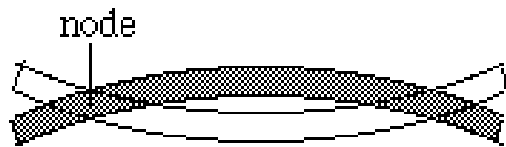




**Ernst Florens  
Friedrich Chladni  
(1756-1827)**

# FIGURE DI CHLADNI

Riscopre le figure di R. Hooke (1680)  
(cfr. Faraday)

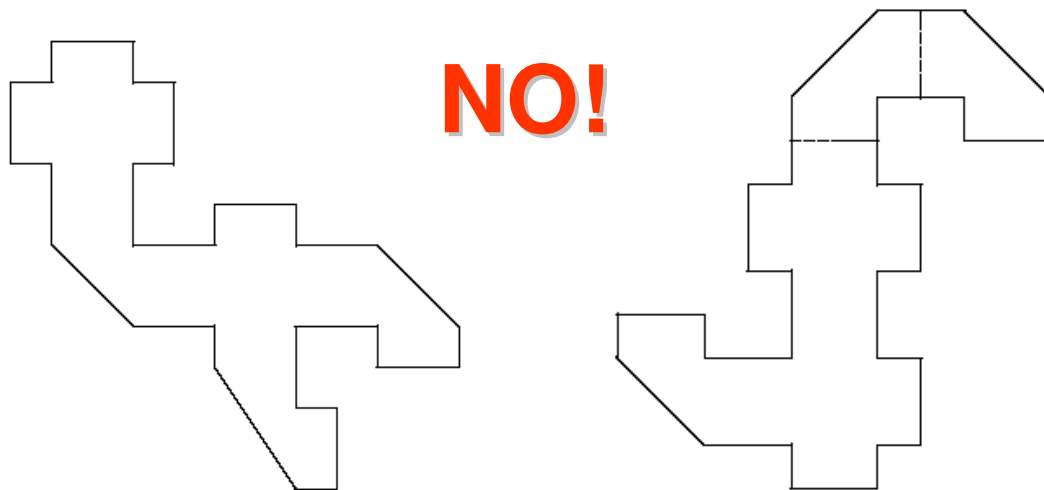


# Si puo' sentire la forma di un tamburo?

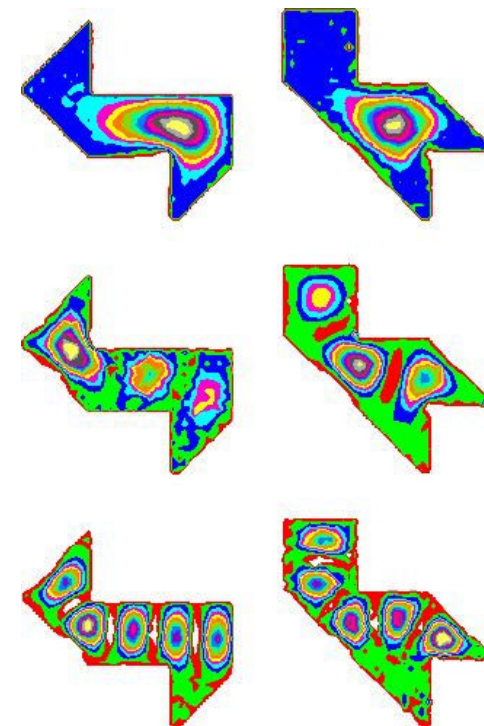
*Can one hear the shape of a drum?*  
American Mathematical Monthly (1966)



**Mark Kac**  
(1914-1984)



C. Gordon, D. L. Webb, S. Wolpert.  
*Isospectral plane domains and surfaces  
via Riemannian orbifolds*  
Inventiones mathematicae (1992)

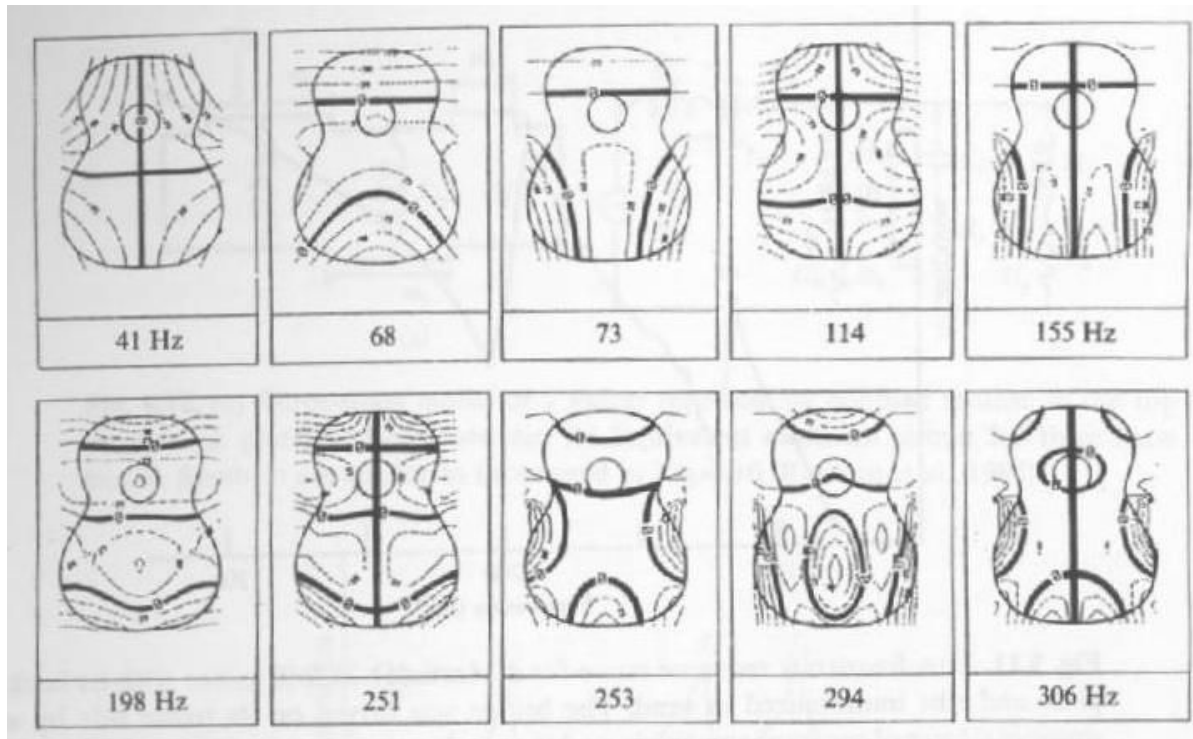


S. Sridhar, A. Kudrolli  
*Experiments on not "hearing  
the shape" of drums.*  
*Physical Review Letters*  
(1994)

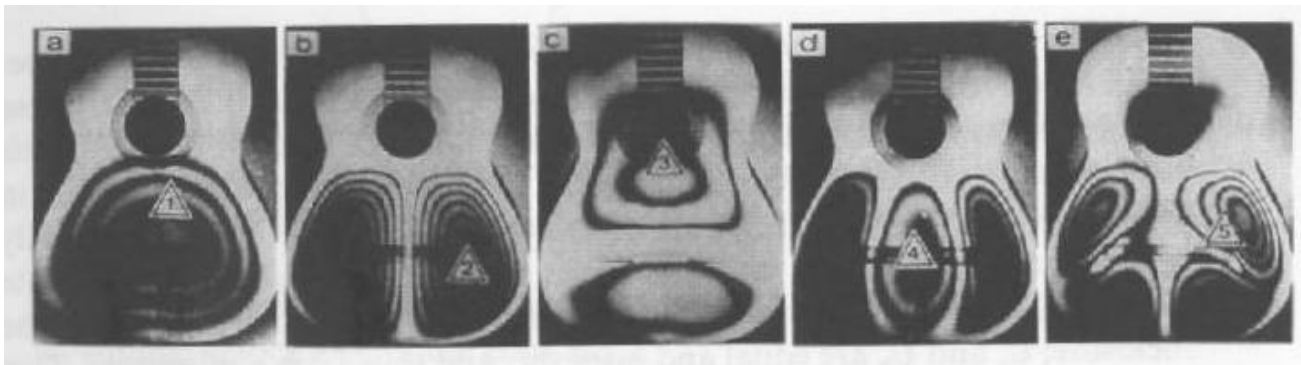


# STRUMENTI A CORDA

# CHITARRA



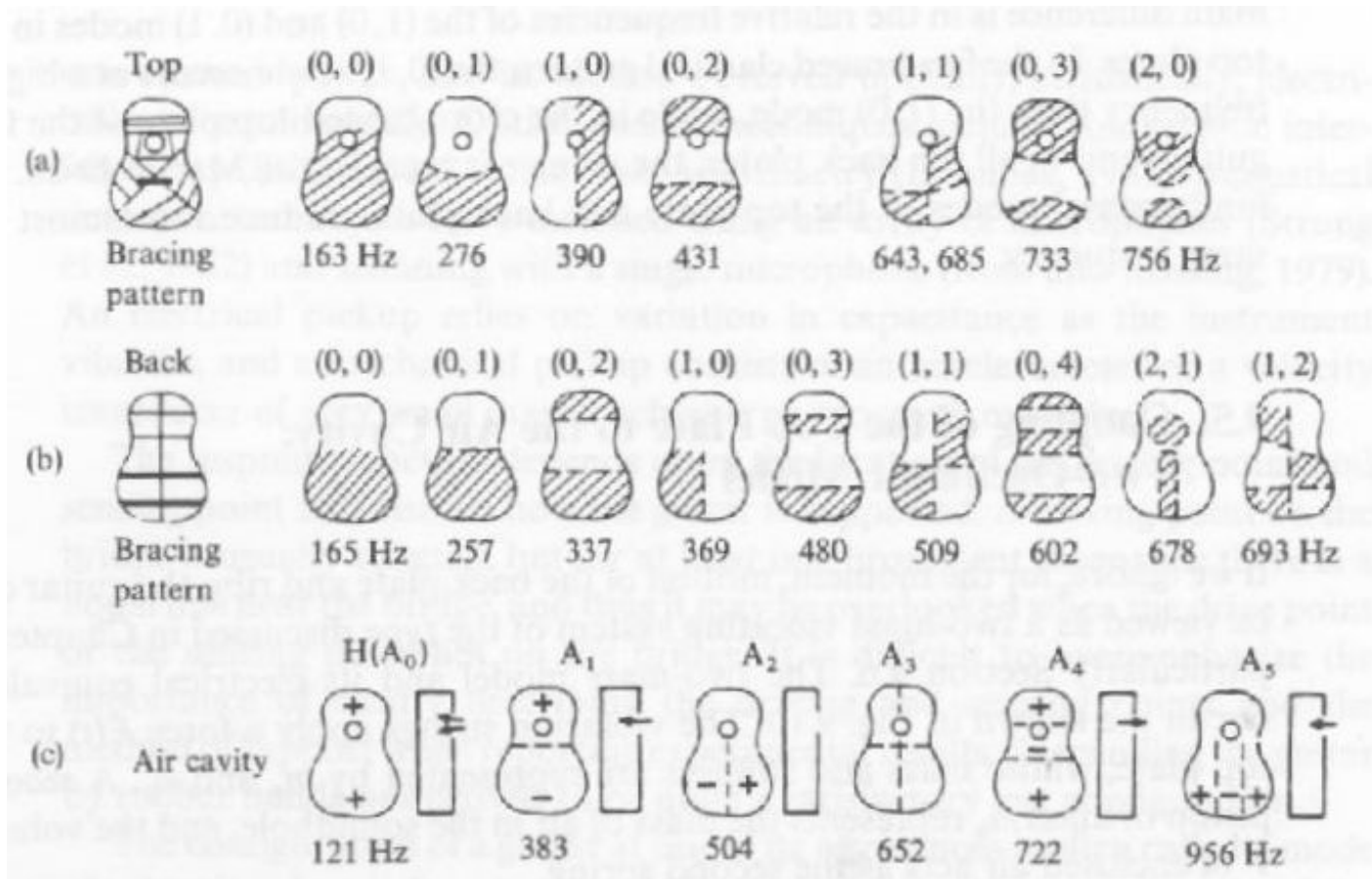
Modi di vibrazione della parte superiore di una chitarra classica con rinforzi



Modi di vibrazione della parte superiore senza il retro della cassa



# CHITARRA



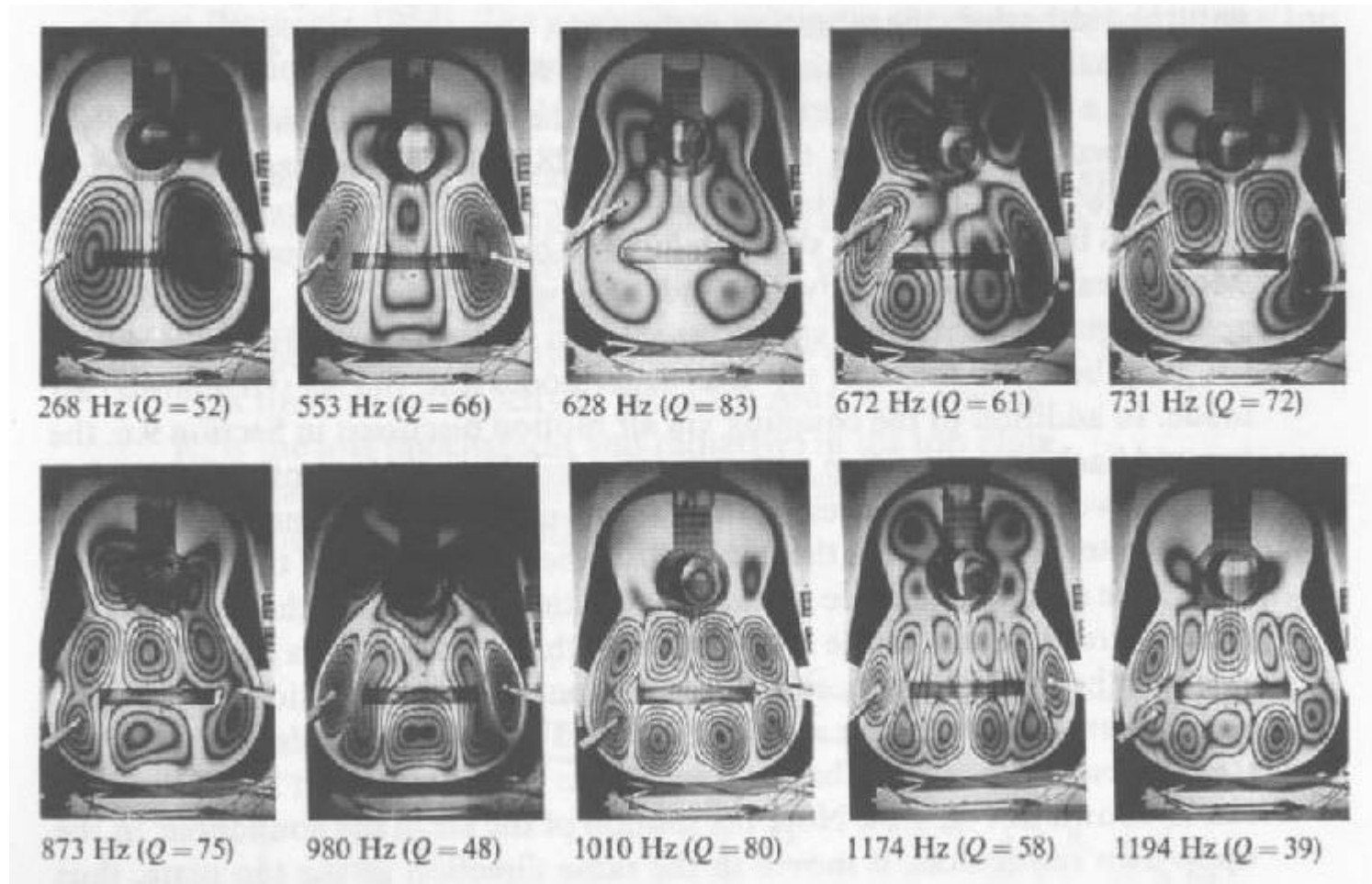
Parte superiore

Parte inferiore

Cavita'

Modi di vibrazione di parti di una chitarra

# CHITARRA

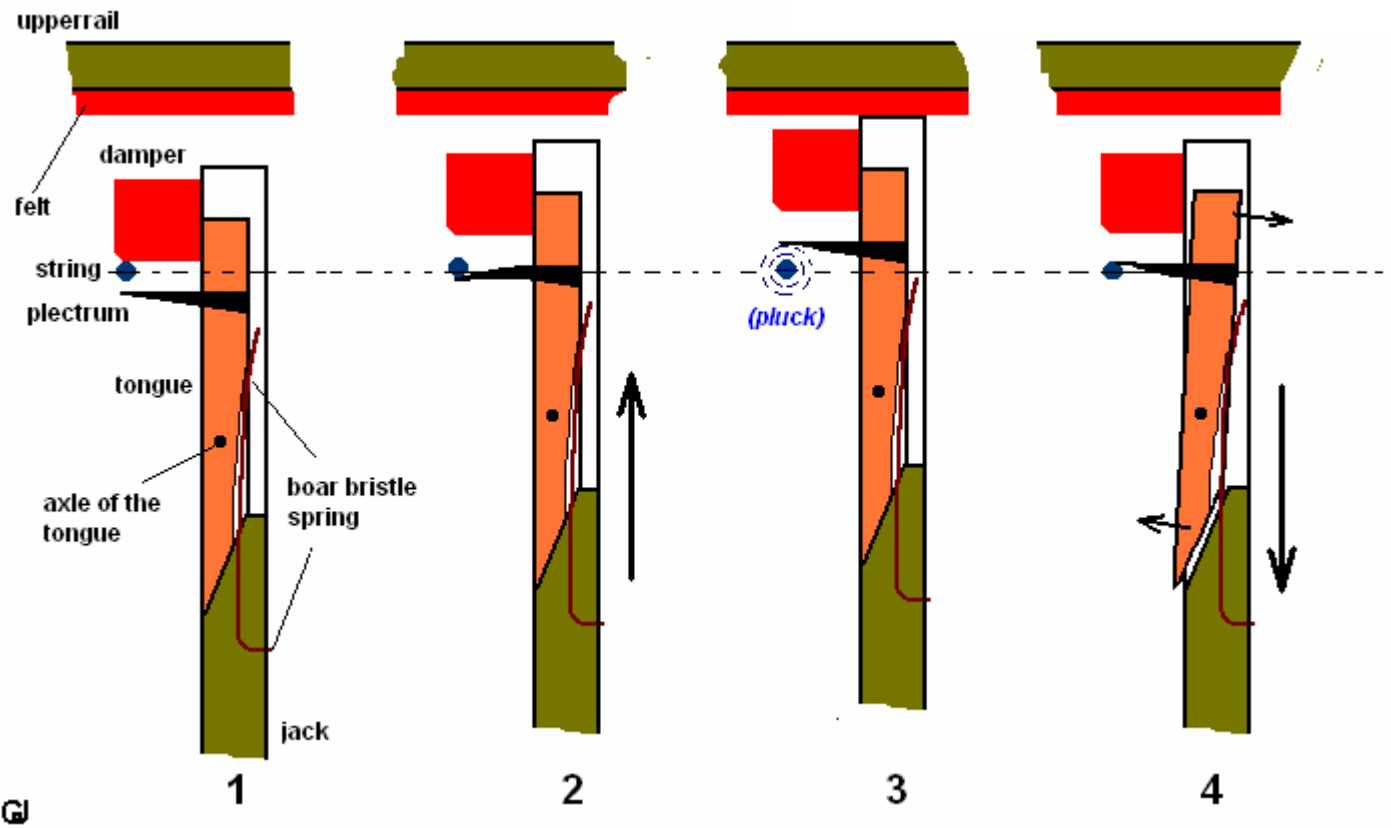
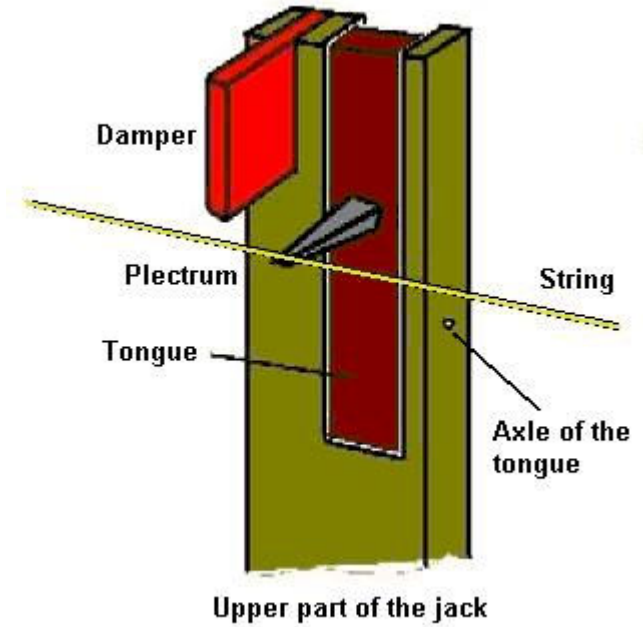


Modi di vibrazione della parte superiore di una chitarra classica

# CLAVICORDO



# CLAVICEMBALO



G

1

2

3

4

# PIANOFORTE



**Bartolomeo  
Cristofori  
(1655-1731)**

Gravicembalo  
col piano e forte



88 tasti: 27.5 Hz (La 0) - 4186 Hz (Do 8)

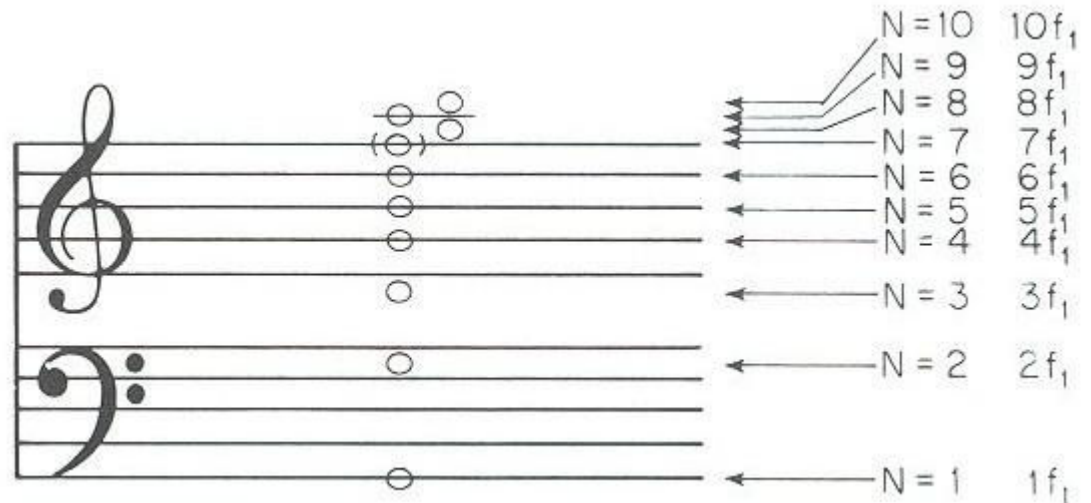
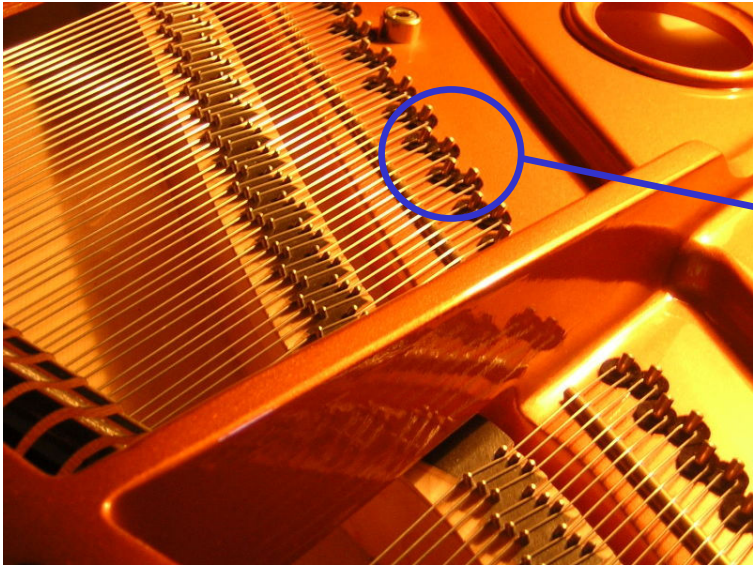
226 corde: 10 x1 + 18 x2 + 60 x3

Rapporti lunghezze/ottava: da 1.88/1 a 1.94/1

Tensione: ~ 30 T

Pedali: “una corda”, “tonale”, “risonanza”

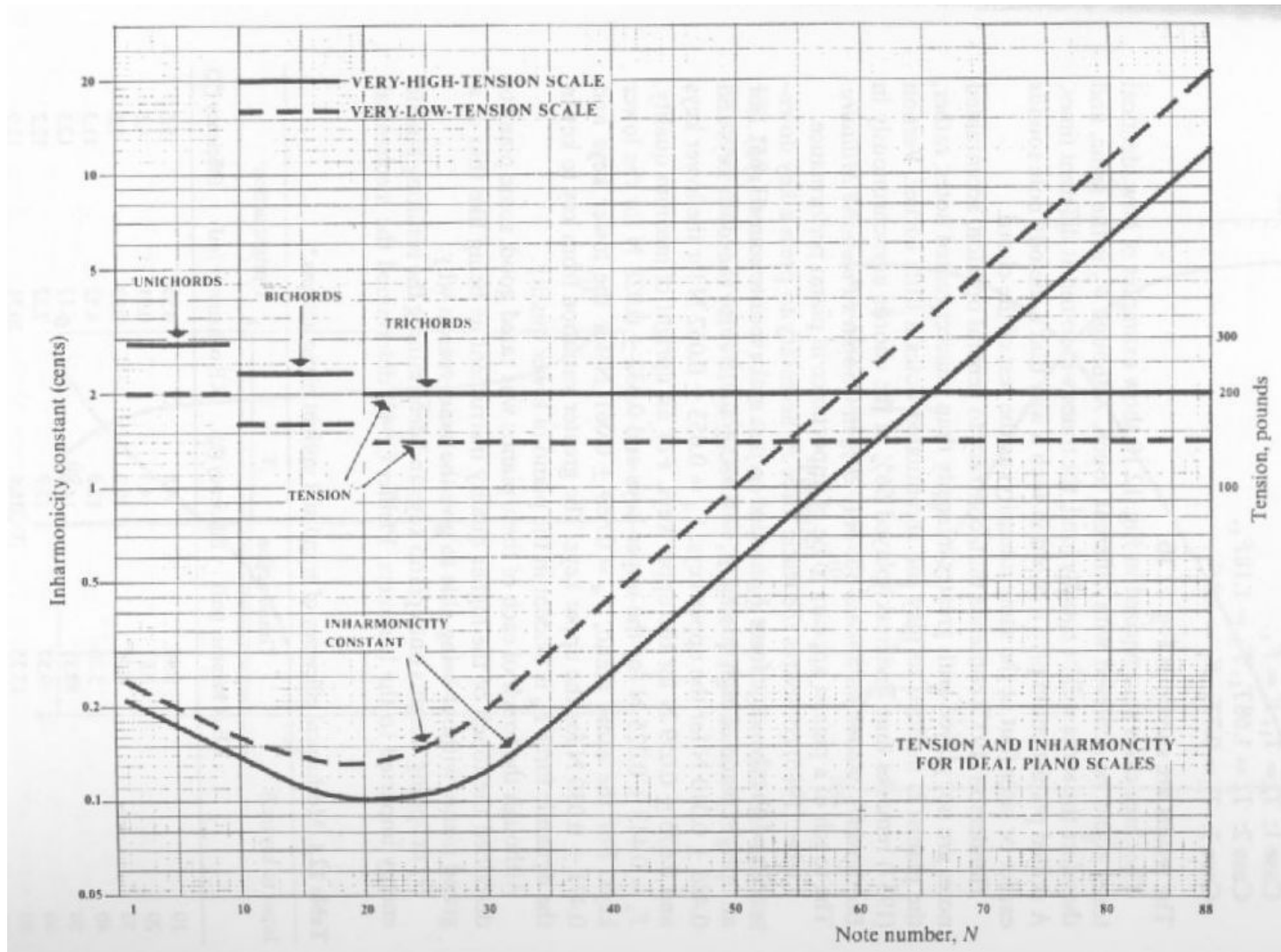
# PIANOFORTE



Il martelletto colpisce la corda ad una distanza  $1/7$  (basso) –  $1/20$  (alto) dall'estremità'.

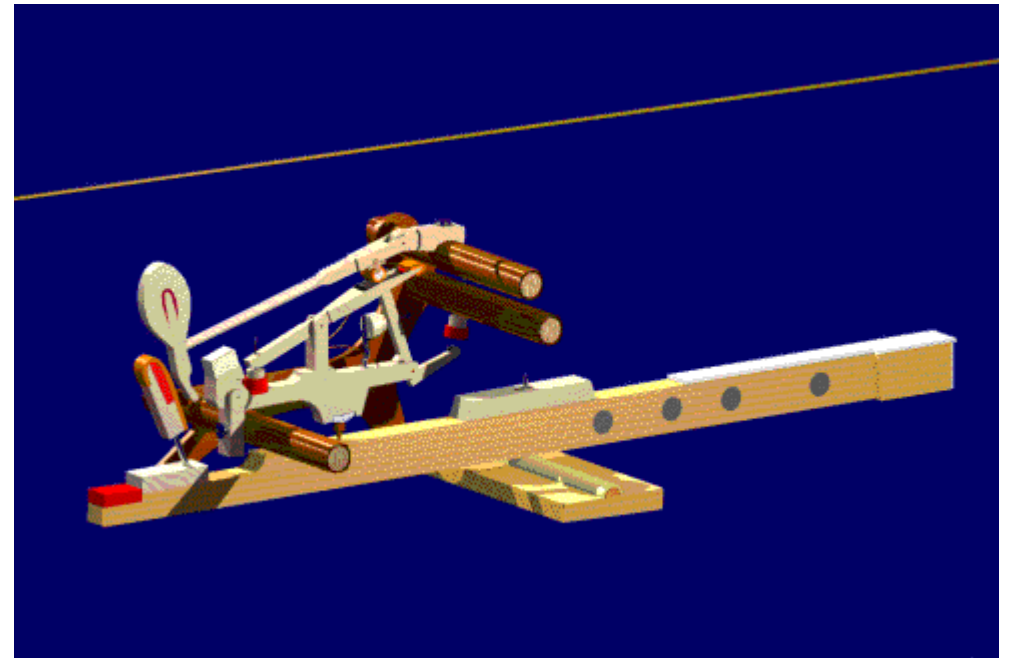
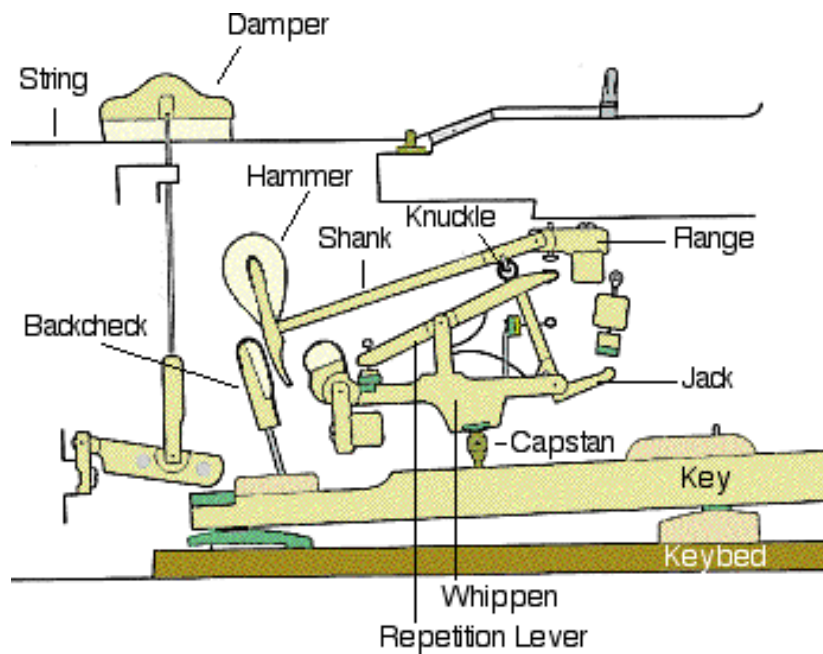


# PIANOFORTE



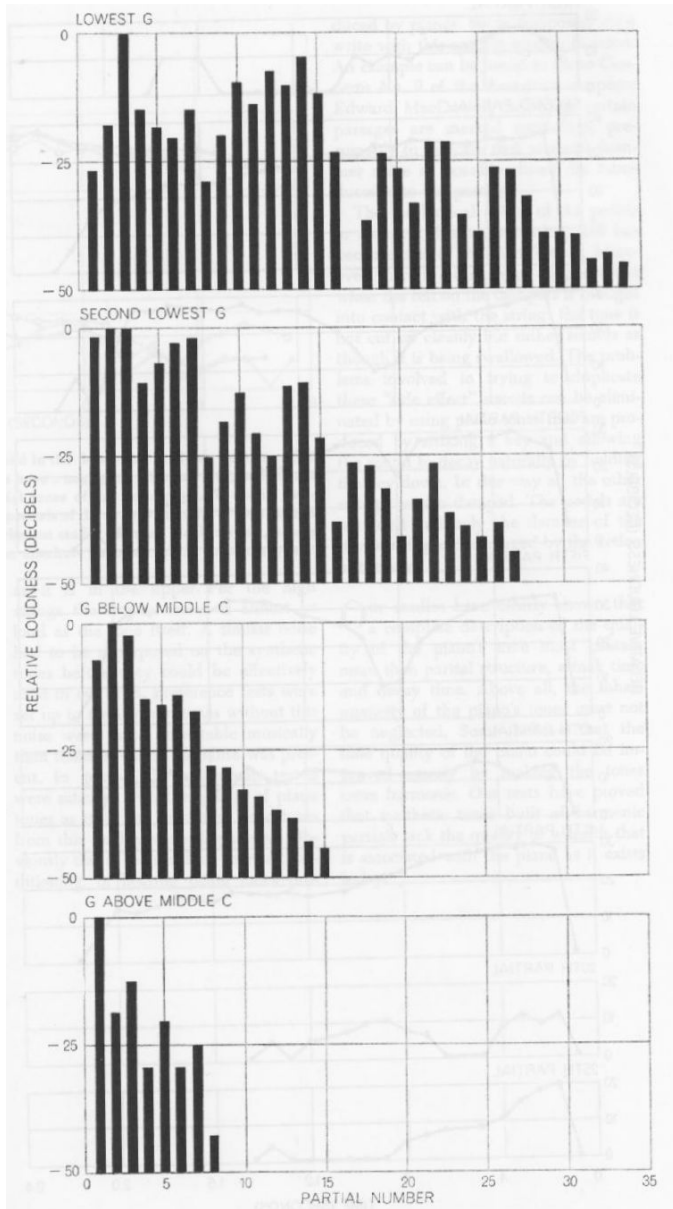
Variazione della tensione e dell'inarmonicita'

# PIANOFORTE

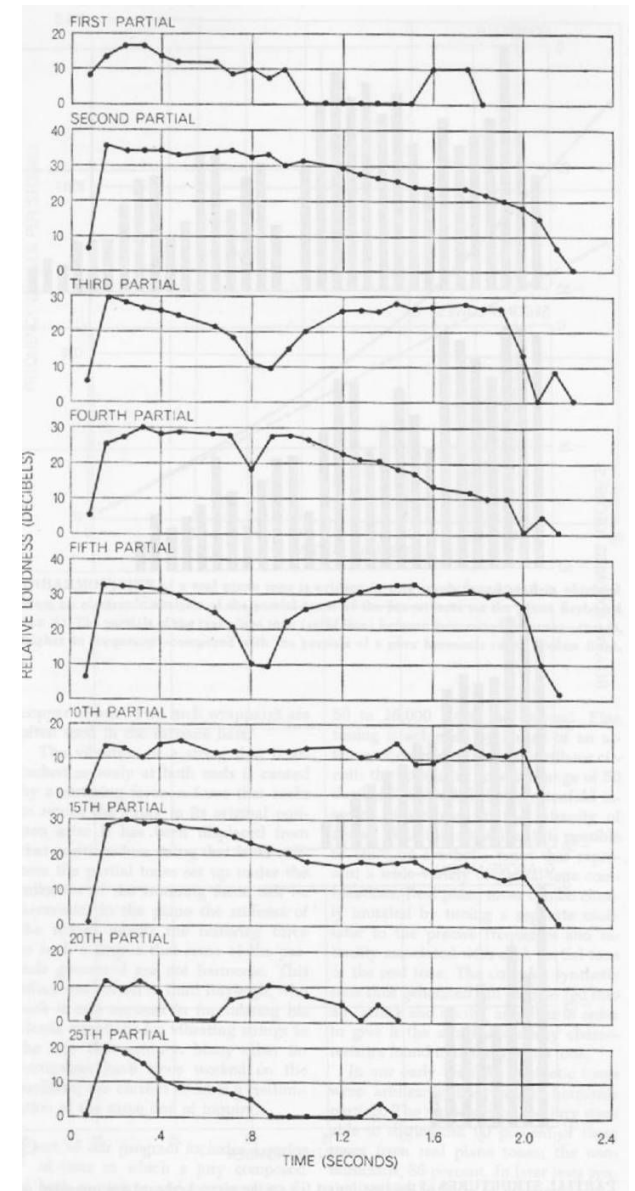


© K. Wayne Land

# PIANOFORTE



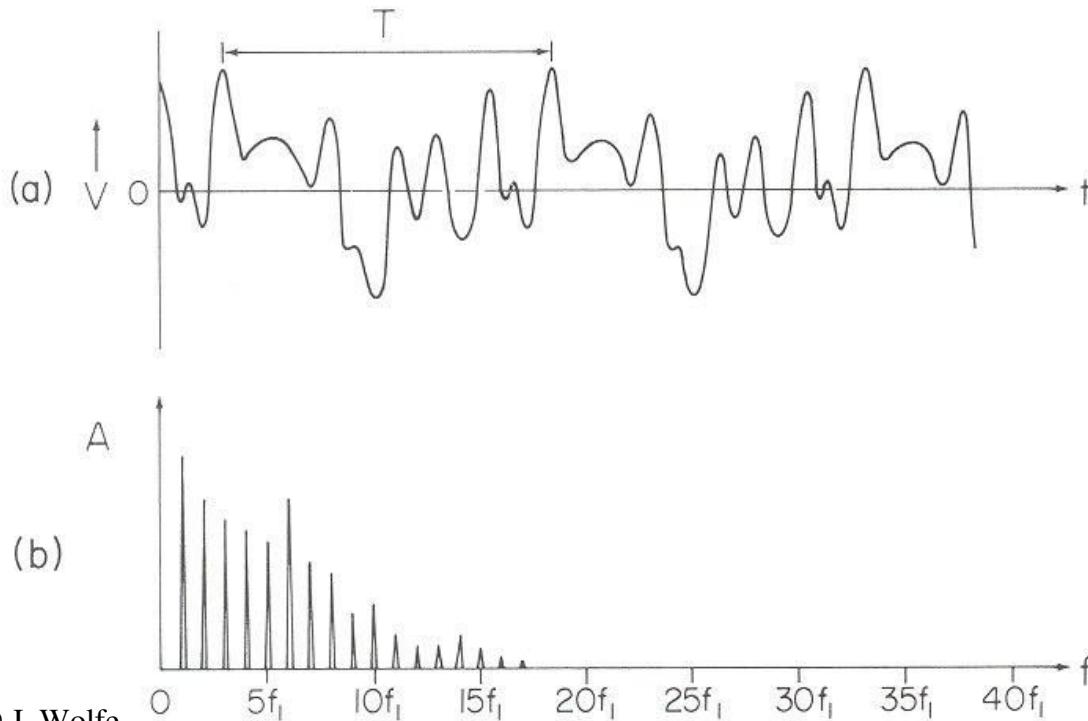
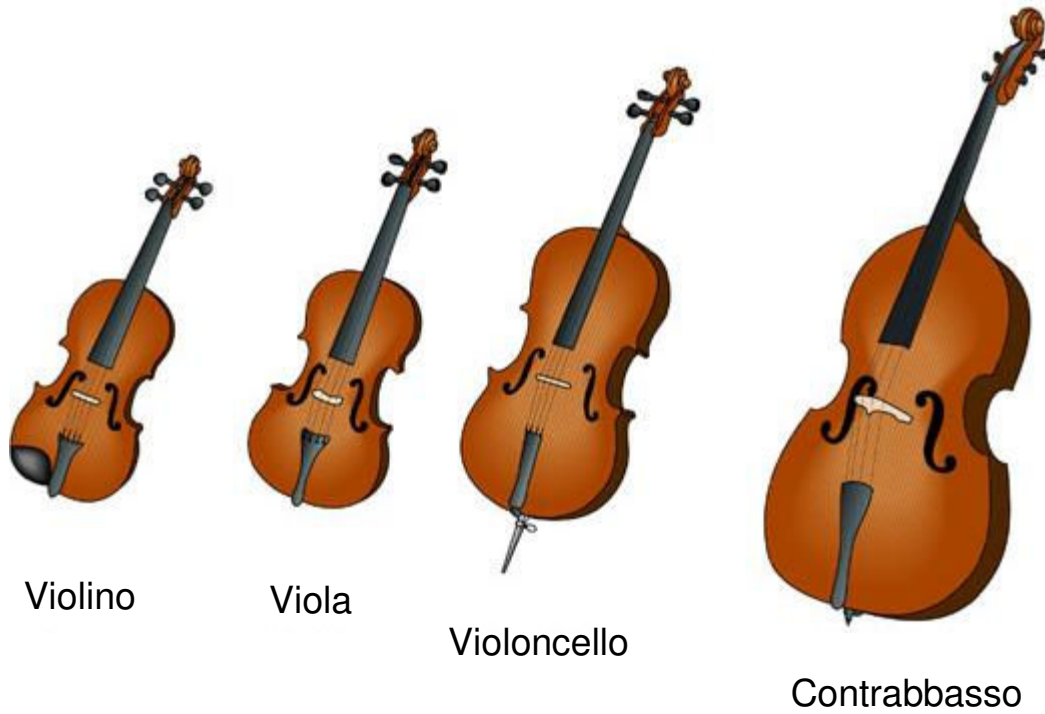
Struttura armonica dei primi quattro SOL di un pianoforte



Evoluzione temporale di alcune armoniche

# STRUMENTI AD ARCO

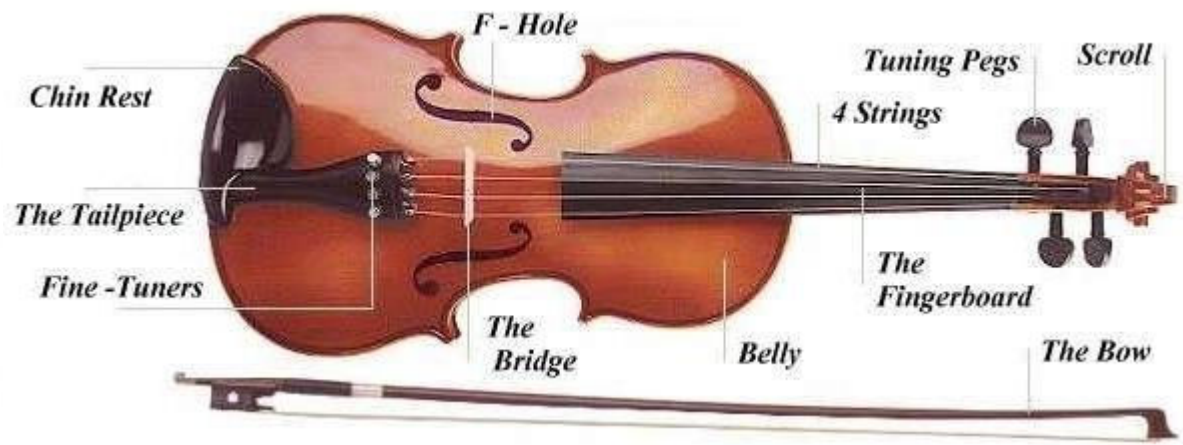
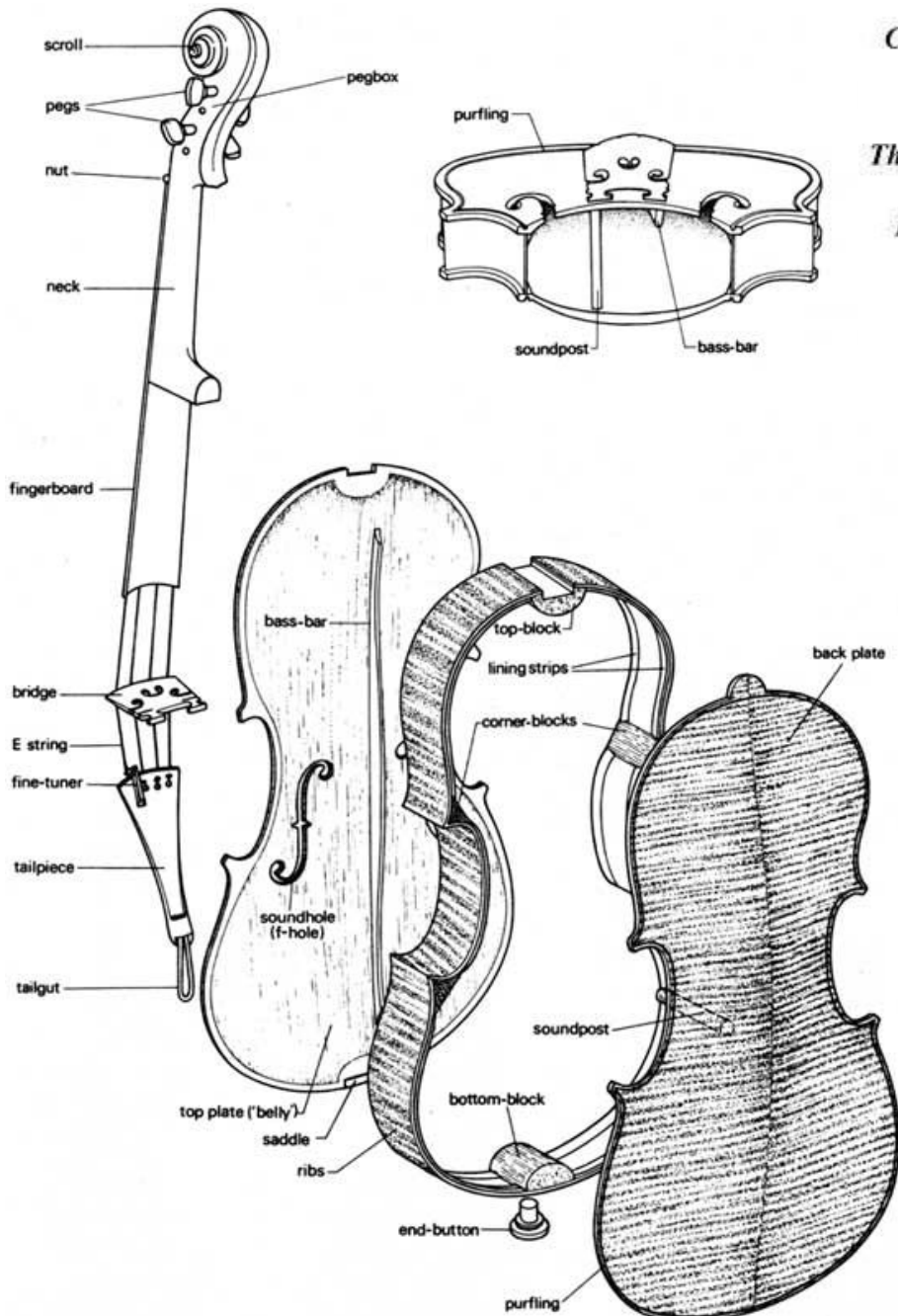
# ARCHI



© J. Wolfe

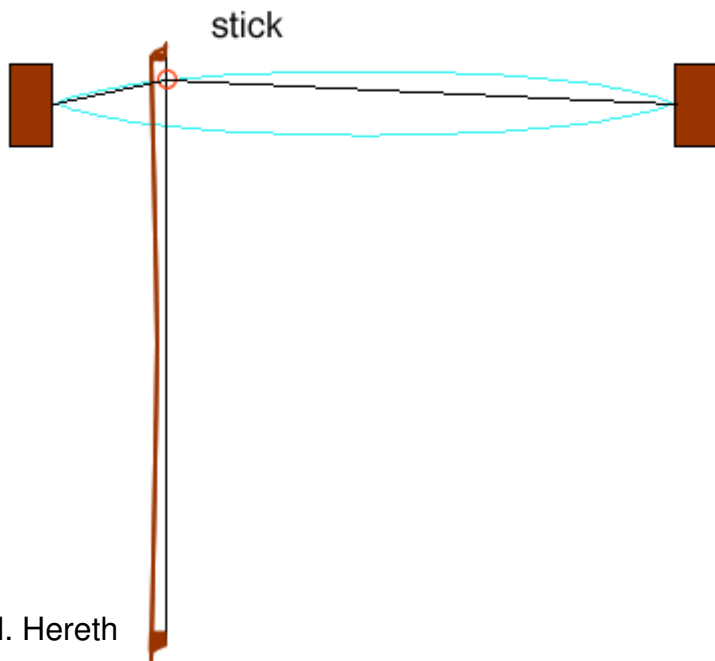


# VIOLINO

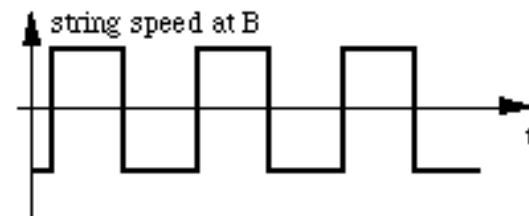
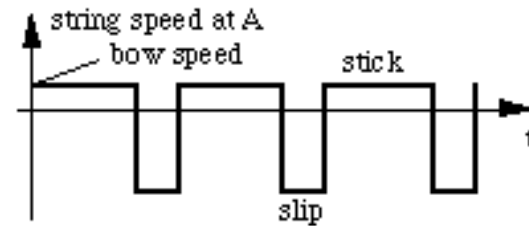
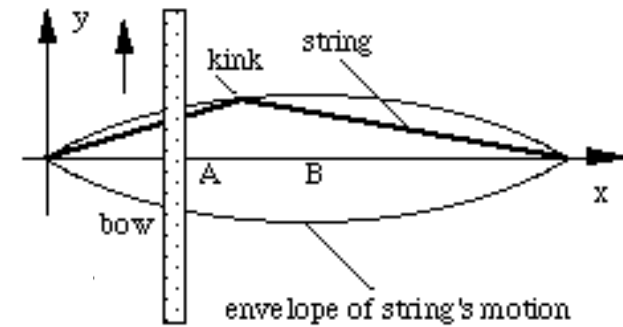


# MOTO DI HELMHOLTZ (1)

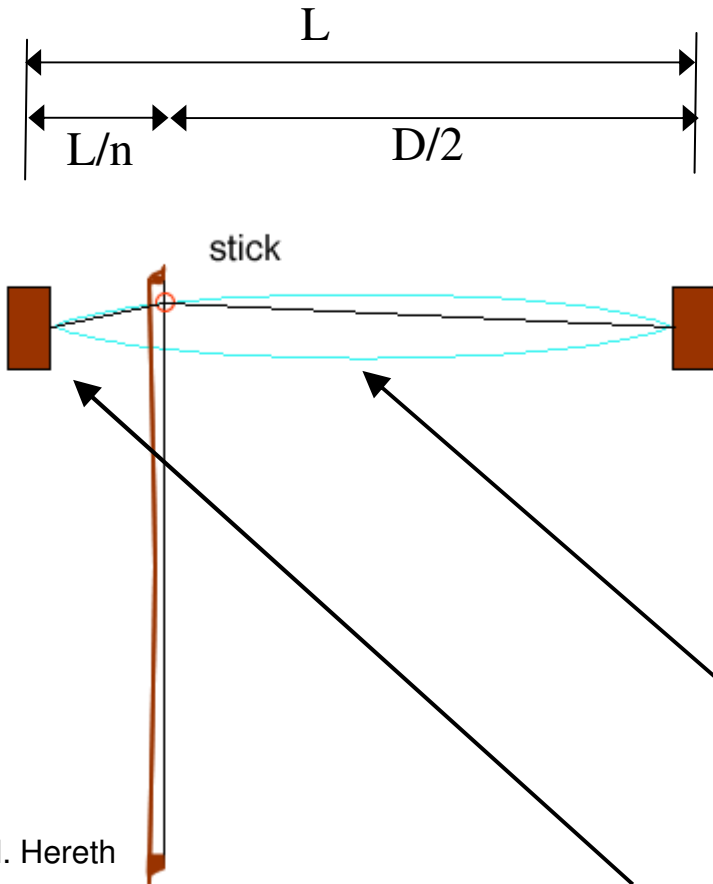
Apporto continuo di energia



© H. Hereth



# MOTO DI HELMHOLTZ (2)



© H. Hereth

Velocita' cuspidale

$$v_c = 2Lf$$

Percorso cuspidale (a dx)

$$D = 2L \frac{n-1}{n}$$

Tempo di adesione

$$t = \frac{D}{v_c} = \frac{n-1}{nf}$$

Ampiezza (adesione)

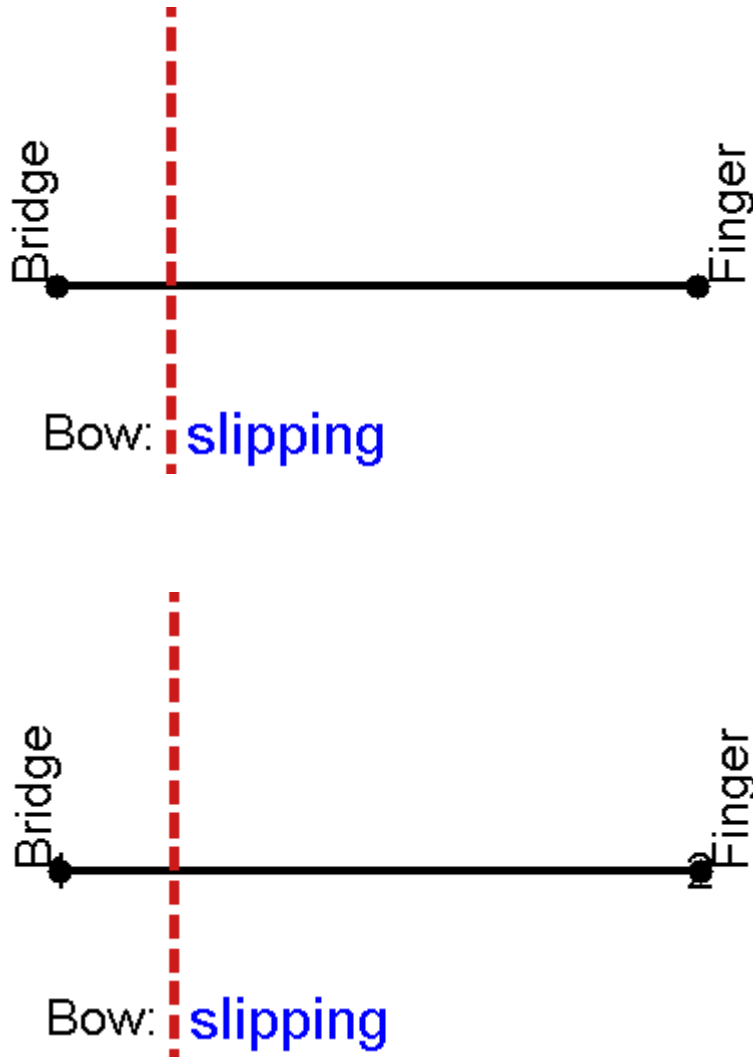
$$A = v_a t = v_a \frac{n-1}{nf}$$

$$A = v_a / f$$

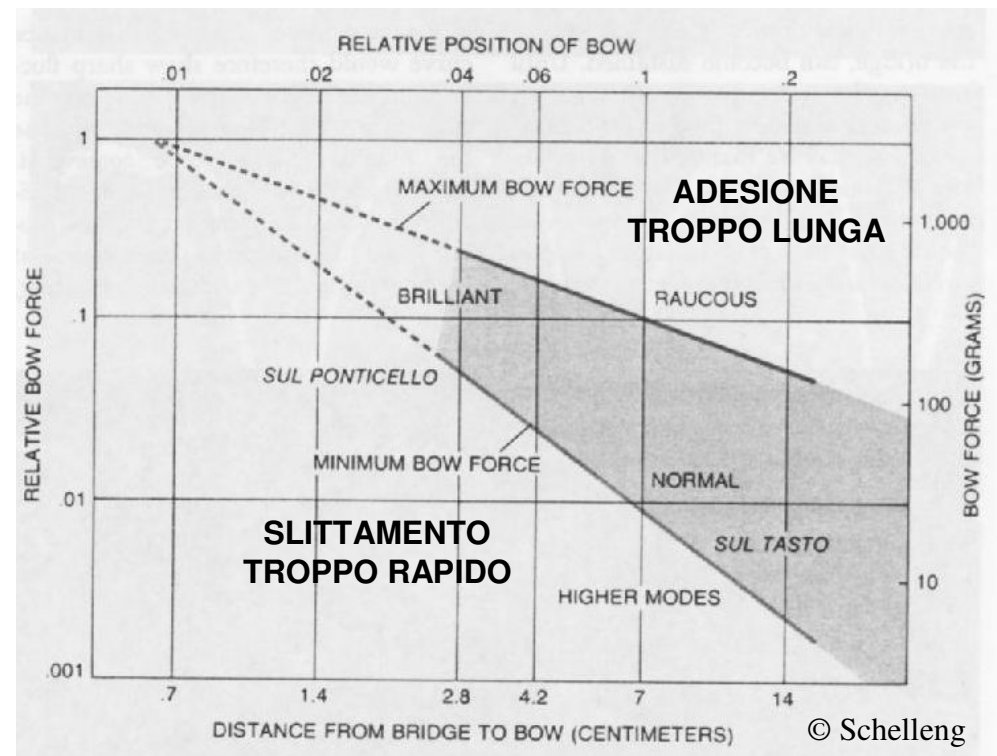
$$A = v_a / 2f$$



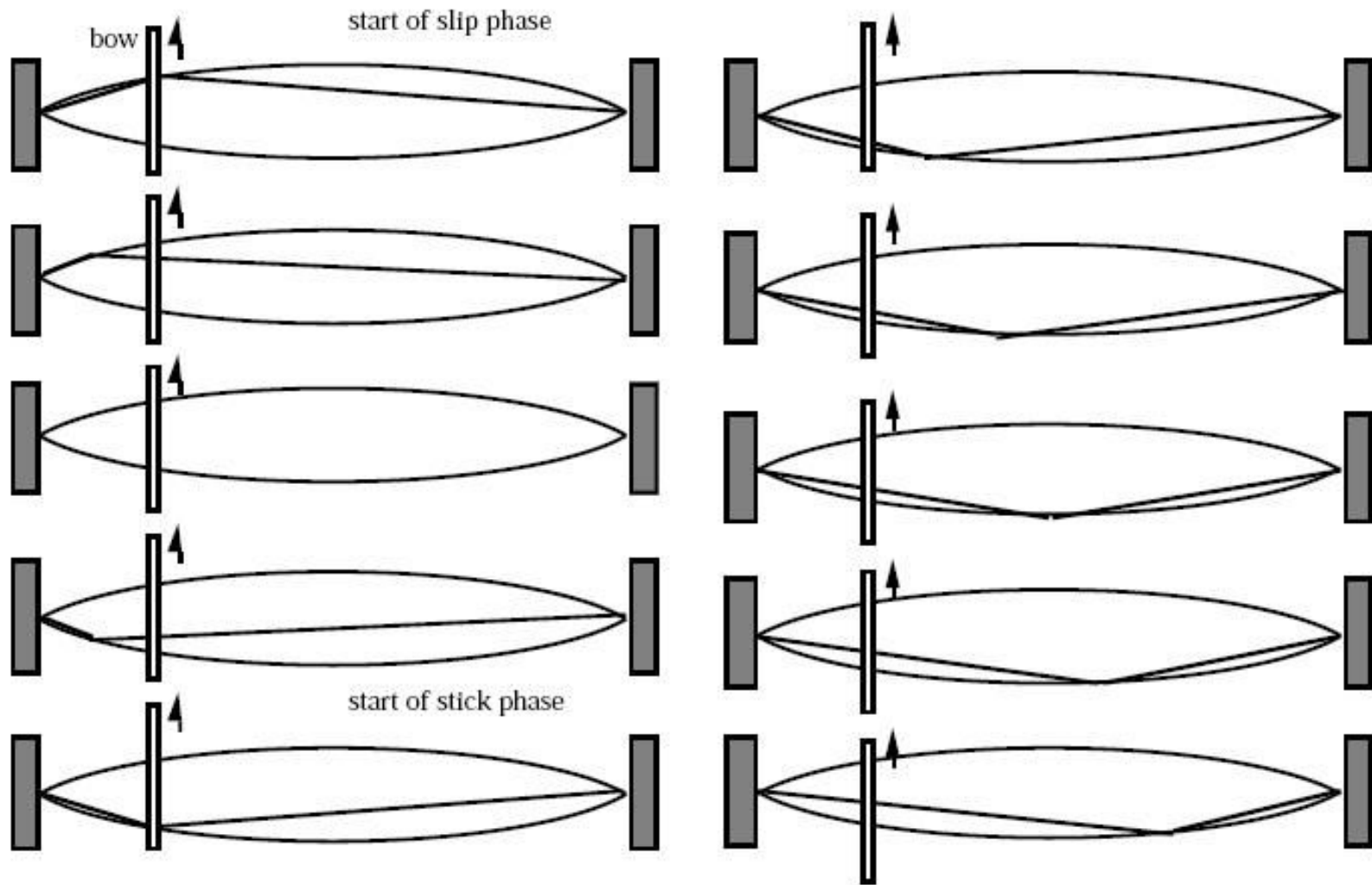
# MOTO DI HELMHOLTZ (3)



Forza applicata sull'archetto a diverse distanze dal ponticello

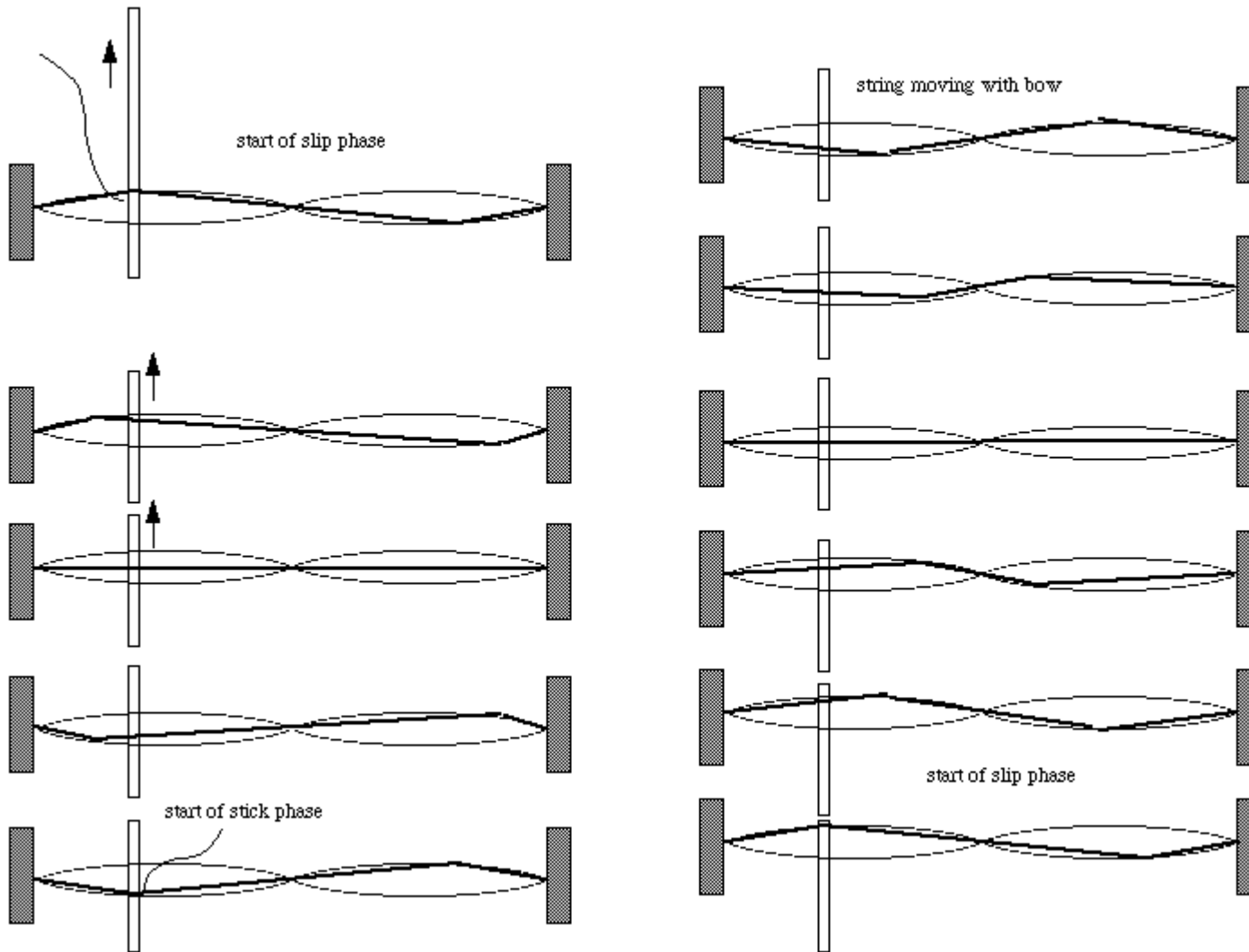


# STRUMENTI AD ARCO (1)



Prima armonica

# STRUMENTI AD ARCO (2)



**Seconda armonica:** due vertici simultanei separati di  $L/2$

# STRUMENTI AD ARCO: ARTICOLAZIONE (1)



**Col legno** (retro dell'archetto, transiente percussivo, smorzamento rapido)



**Colle'** (parte inferiore dell'archetto)



**Pizzicato** (impulsivo, smorzamento rapido)



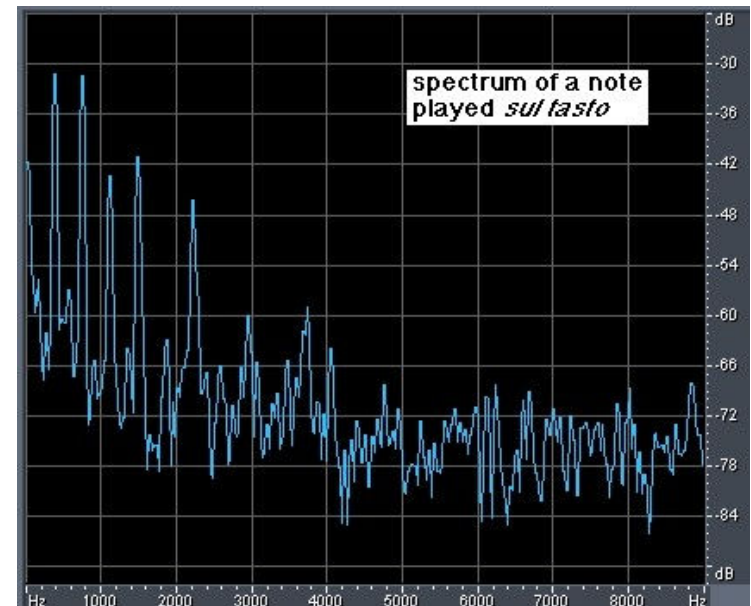
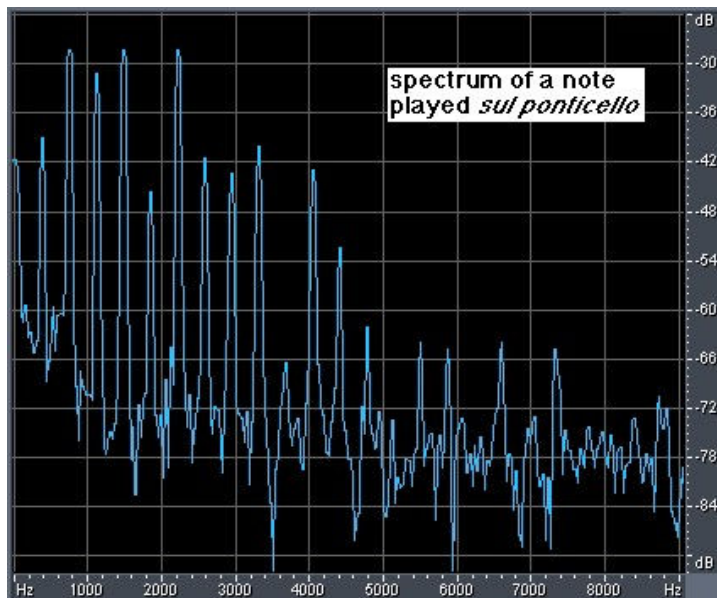
**Spiccato** (percussivo, rimbalzo)



**Sul ponticello** (irregolare, armoniche)



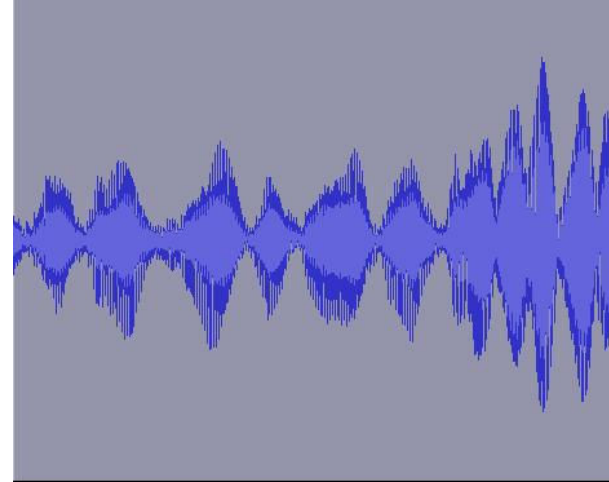
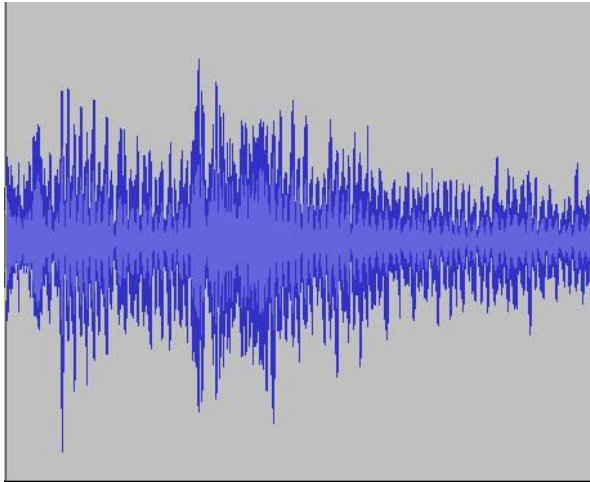
**Sul tasto** (debole, poche armoniche)



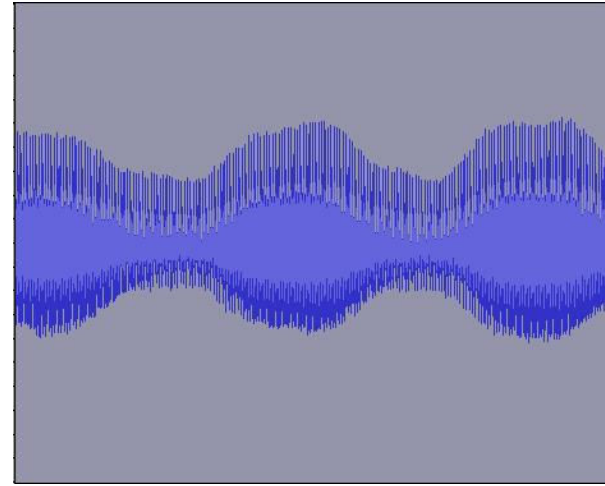
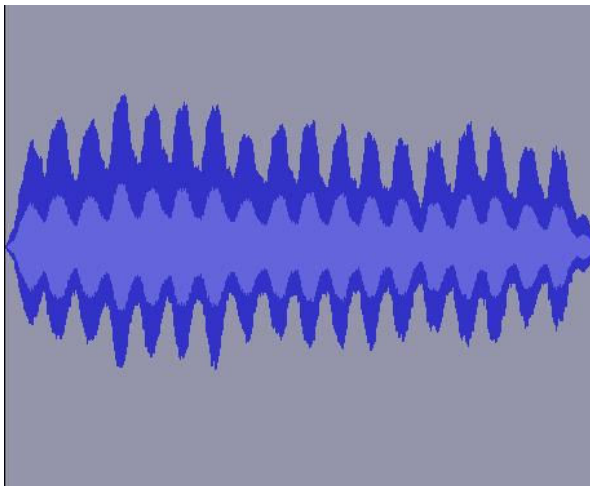
# STRUMENTI AD ARCO: ARTICOLAZIONE (2)



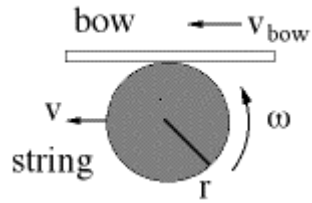
**Tremolo** (variazione direzione del moto)



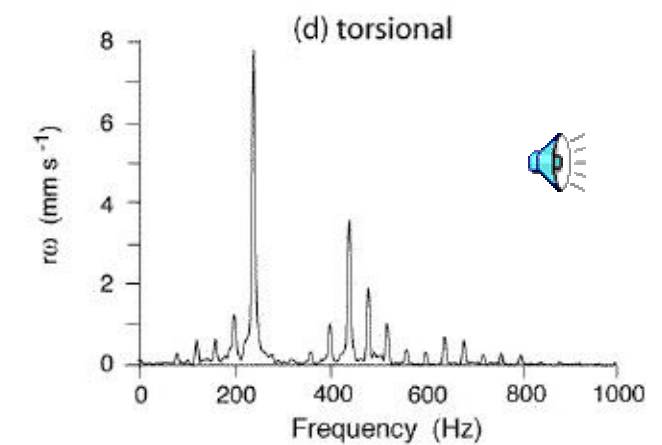
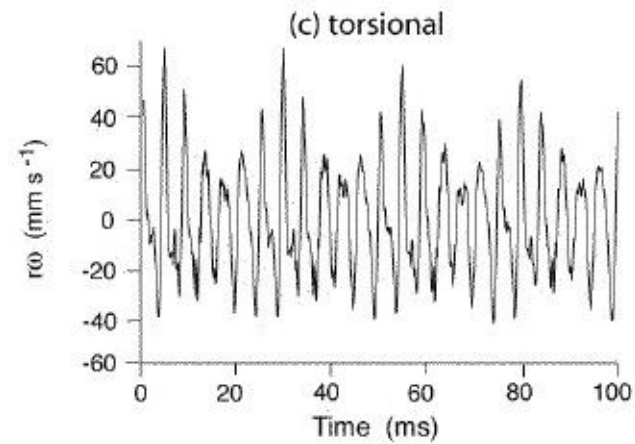
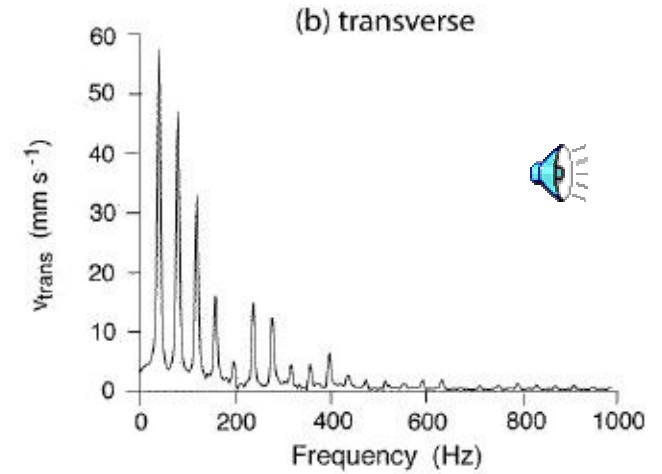
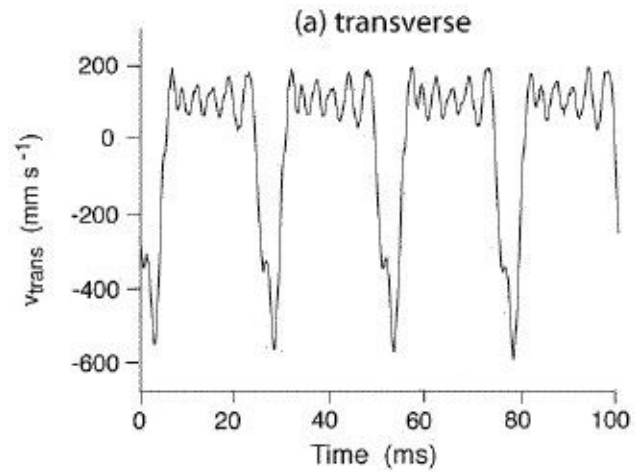
**Vibrato** (variazione lunghezza e tensione corda)  
Forte interazione con la risposta del risuonatore



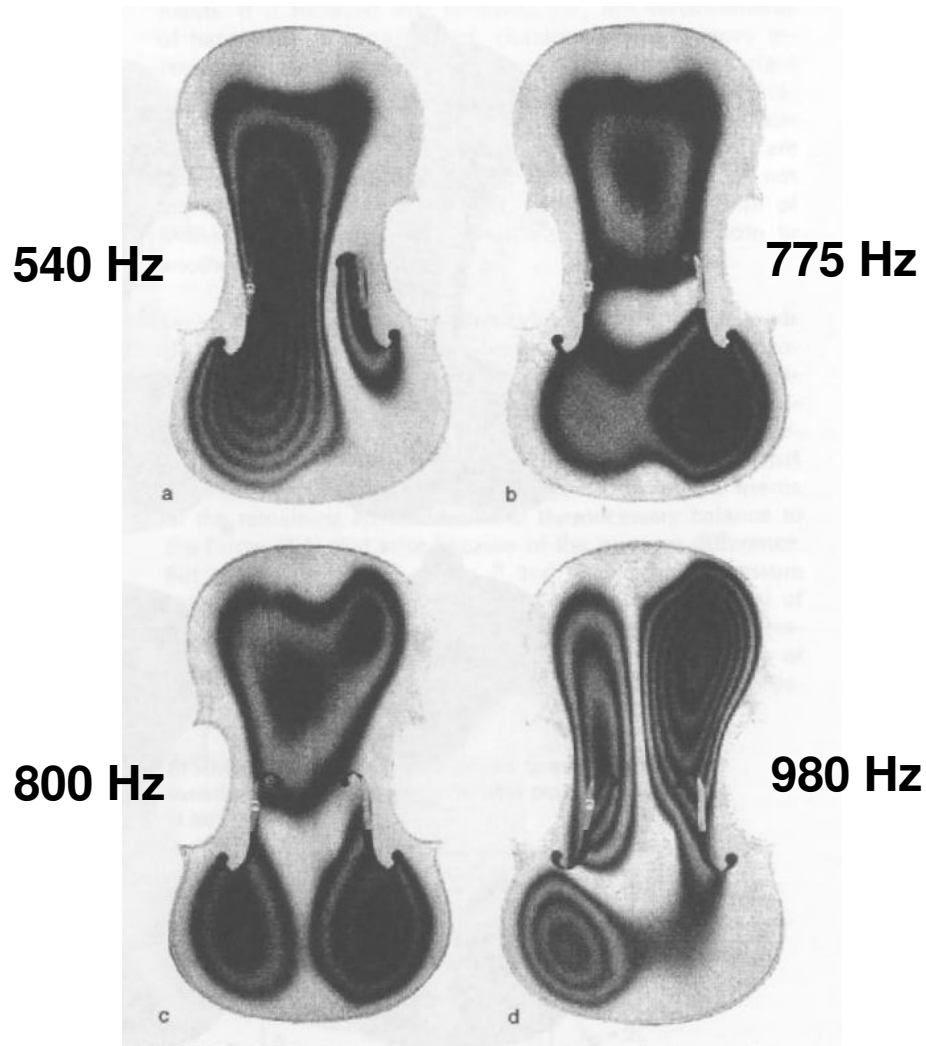
# ONDE DI TORSIONE



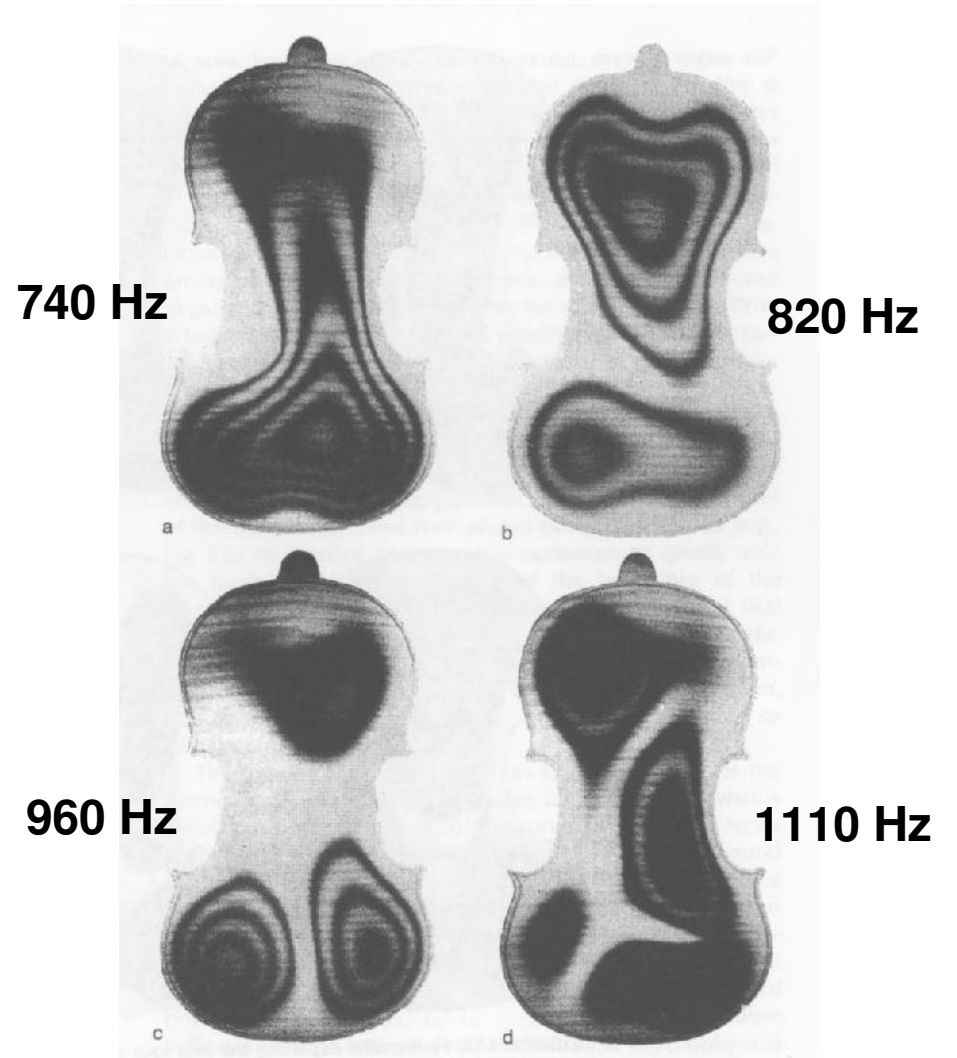
Contributo del 10%  
alla velocità relativa



# VIOLINO: MODI PROPRI

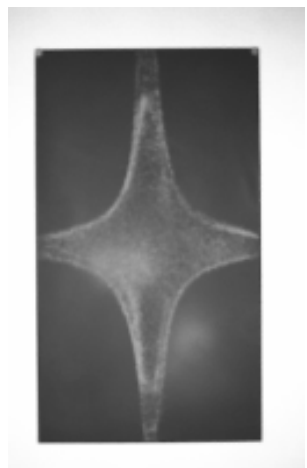


Parte superiore di un violino

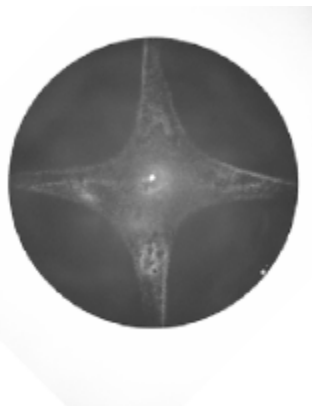


Parte inferiore di un violino

# VIOLINO: MODI PROPRI



Modo (1,1)

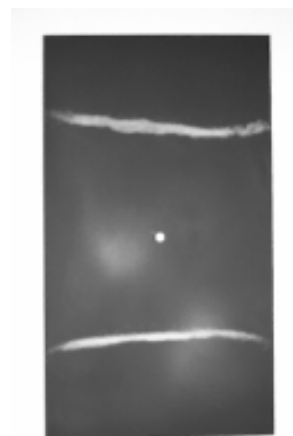


Modo (2,0)



Modo 1

Frequenza minore: 2 linee nodali ortogonali

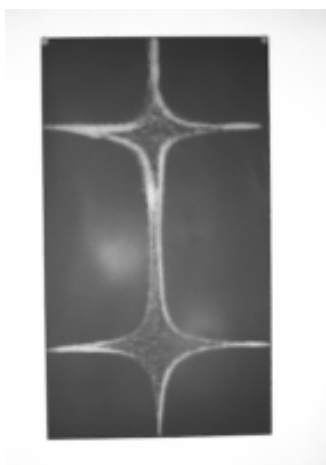


Modo (0,2)

170 Hz



Modo 2

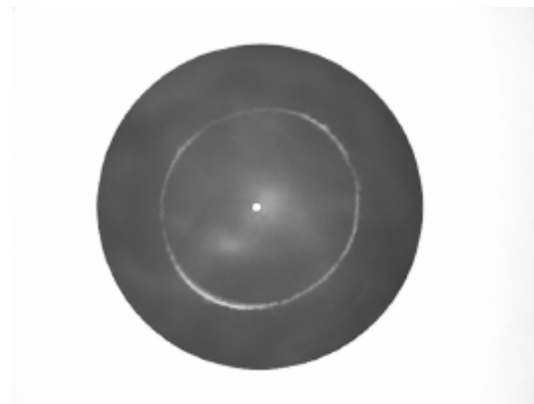


Modo (1,2)

231 Hz



Modo 3



Modo (0,1)

384 Hz



Modo 5



# VIOLINO: MODI PROPRI



77 Hz



145 Hz



235 Hz



243 Hz



299 Hz



312 Hz



91 Hz



138 Hz



196 Hz



231 Hz



306 Hz

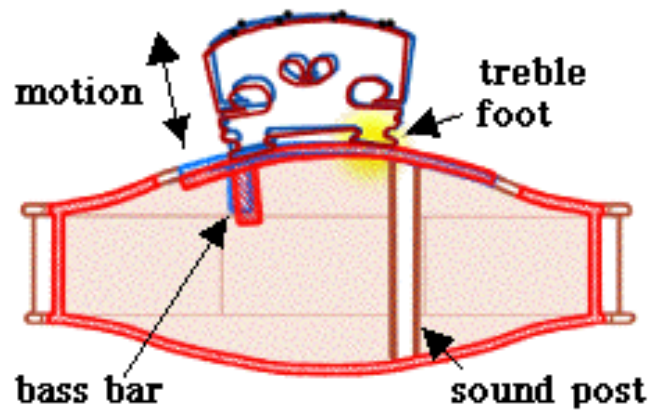


312 Hz

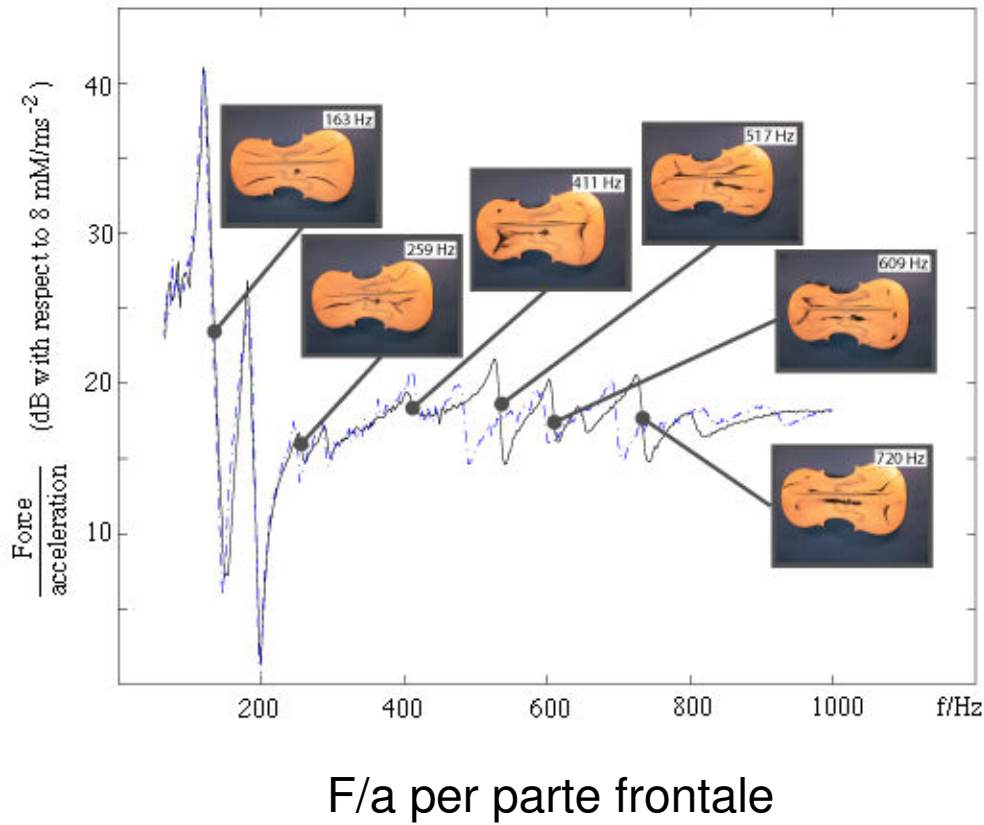


392 Hz

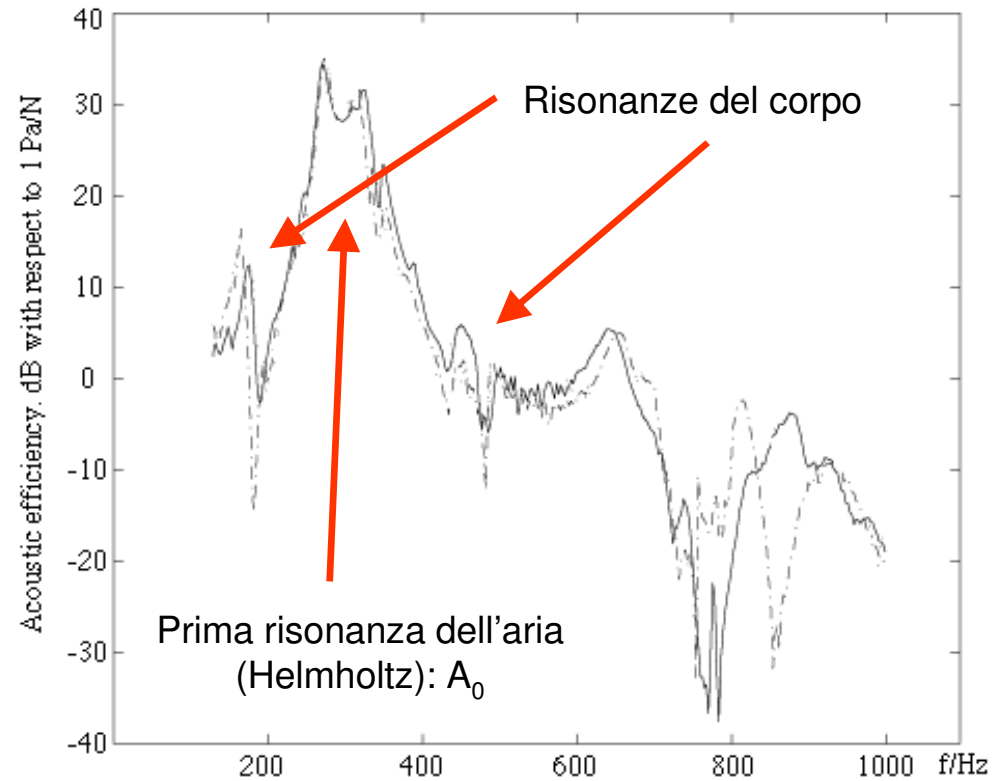
# VIOLINO: ACCOPPIAMENTO



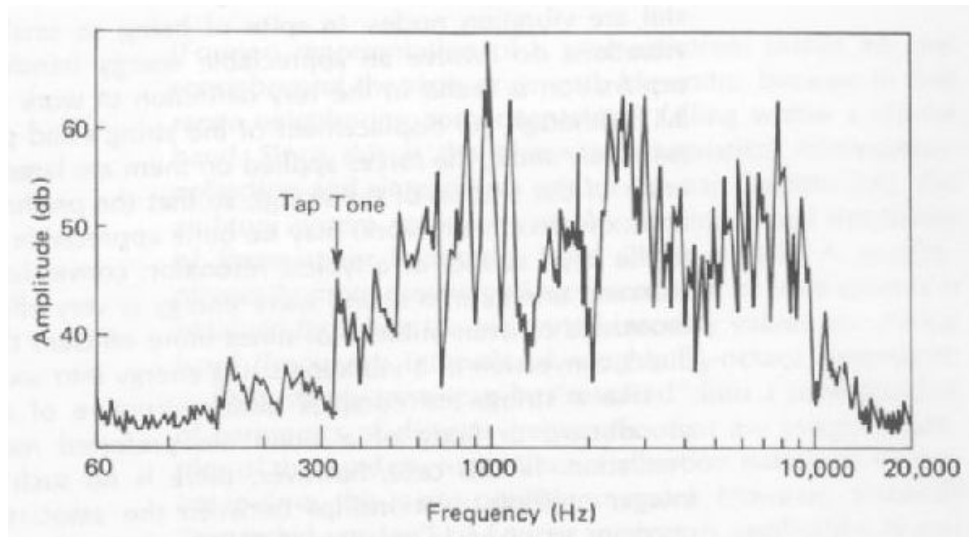
# VIOLINO



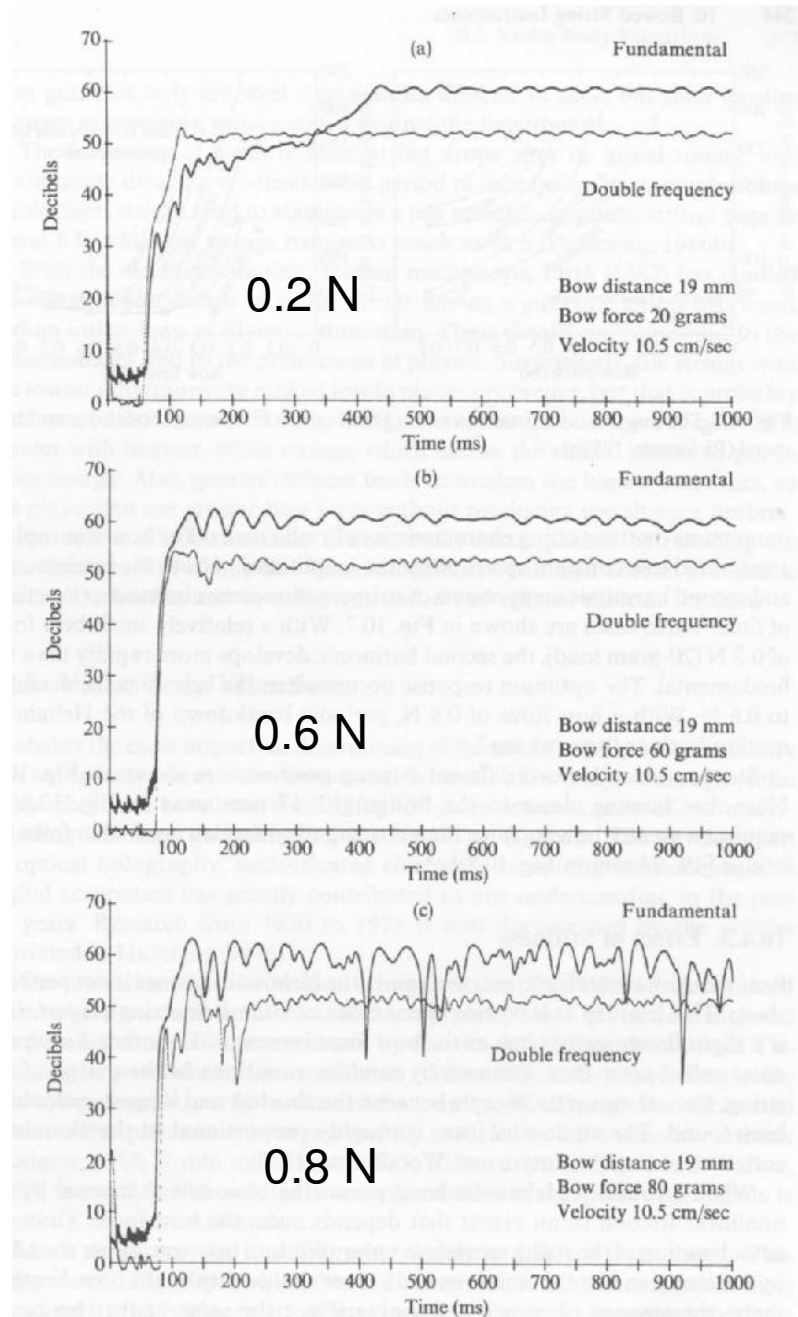
Efficienza acustica (p/F)  
di un violino completo



# VIOLINO



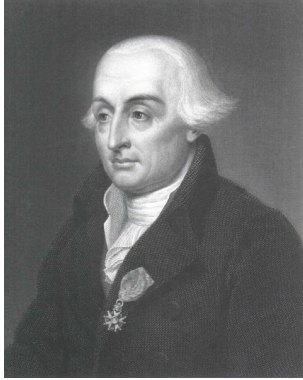
Curva di risonanza di un violino



Caratteristica iniziale di un violino per diversa forza sull'archetto

# ONDE NEI FLUIDI

# RICHIAMI DI FLUIDODINAMICA



**Joseph-Louis Lagrange**  
(1736 - 1813)

**Descrizione Lagrangiana:**  
coordinate di un elemento di  
fluido di cui si segue il moto



**Leonhard Euler**  
(1707-1783)

**Descrizione Euleriana:**  
proprietà' del fluido in un  
elemento di volume fisso

# RICHIAMI DI FLUIDODINAMICA

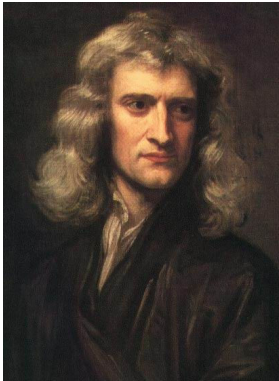


**Claude Louis  
Marie Henri Navier  
(1785 - 1835)**



**Sir George  
Gabriel Stokes  
(1819 - 1903)**

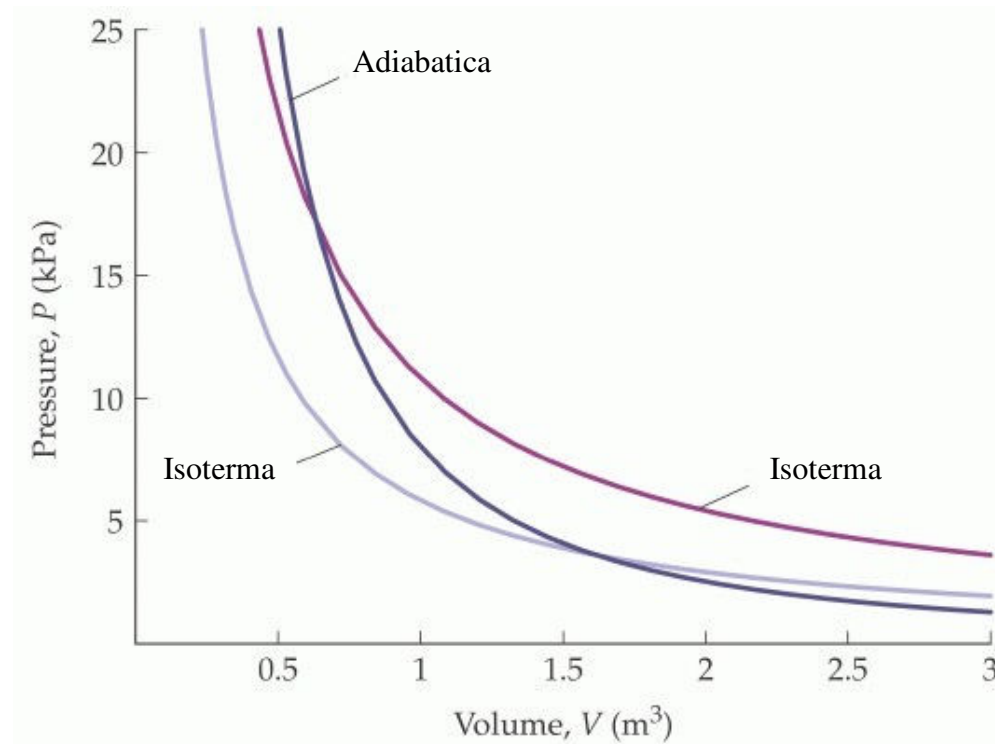
# VELOCITA' DEL SUONO



**Sir Isaac Newton**  
(1643 - 1727)

Isoterma: 298 m/s (scostamento dal valore sperimentale 335 m/s attribuita ad effetti non ideali)

*Principia – Libro II - Proposizione 49*



Adiabatica



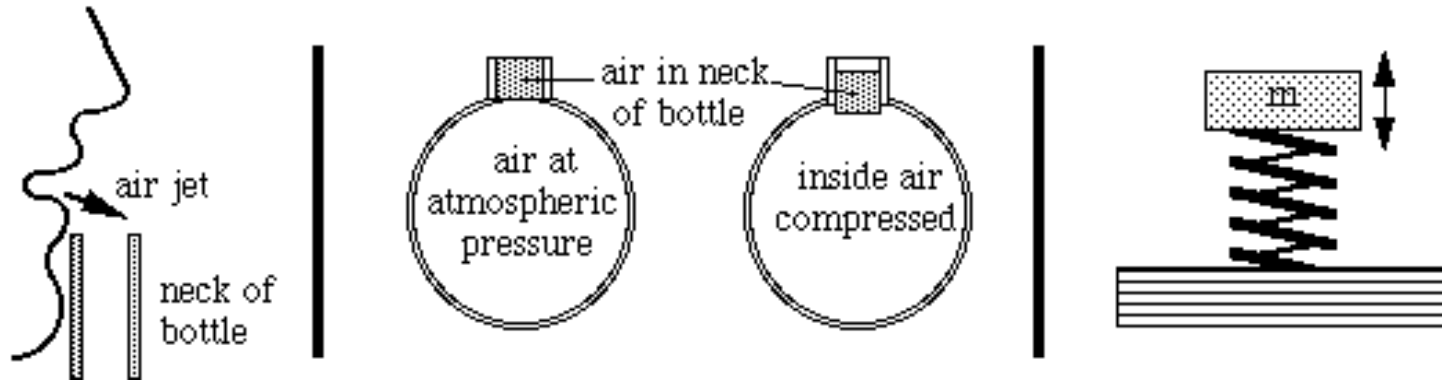
**Pierre-Simon  
marchese di  
Laplace**  
(1749 – 1827)

Dipendenza della frequenza dalla velocità del suono:

- (1) velocità cresce con la temperatura (cfr. strumenti a corda,  $T <$ ,  $v <$ )
- (2) velocità cresce con l'umidità (densità  $>$ , prove)



# RISUONATORE DI HELMHOLTZ



**Hermann Ludwig  
Ferdinand  
von Helmholtz  
(1821-1894)**

$$f = \frac{v}{2\pi} \sqrt{\frac{S}{VL}}$$

$v$  = velocità propagazione  
 $S$  = superficie dell'apertura  
 $V$  = volume  
 $L$  = lunghezza del collo

1863: Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik  
(Sulle sensazioni di tono come base fisiologica per la teoria della musica)

# RISUONATORI DI HELMHOLTZ

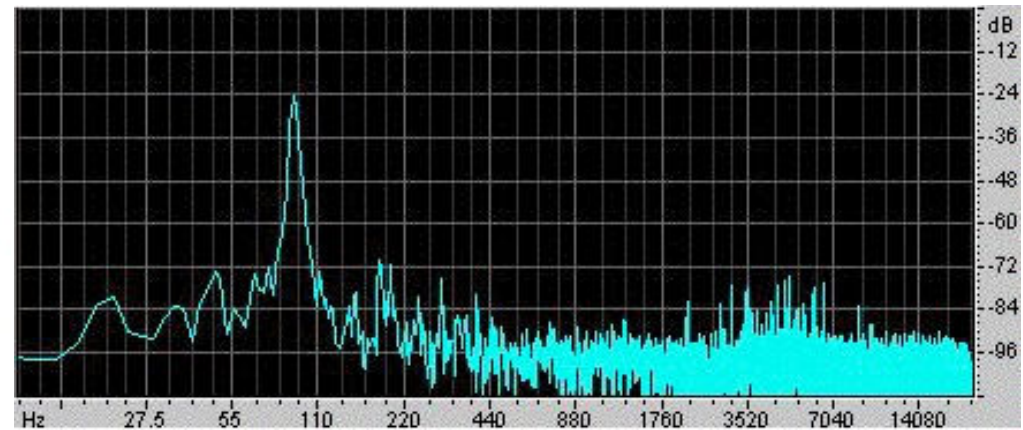
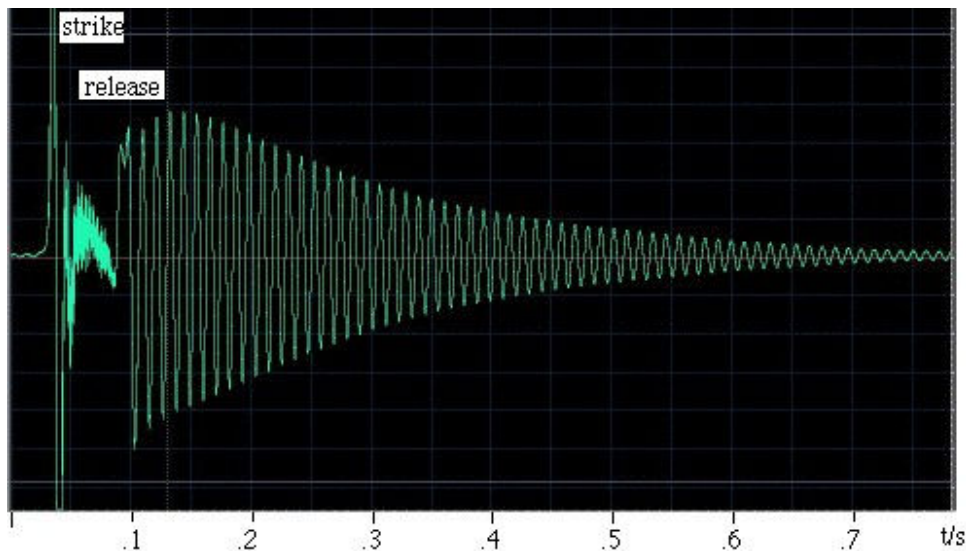


# RISUONATORE DI HELMHOLTZ

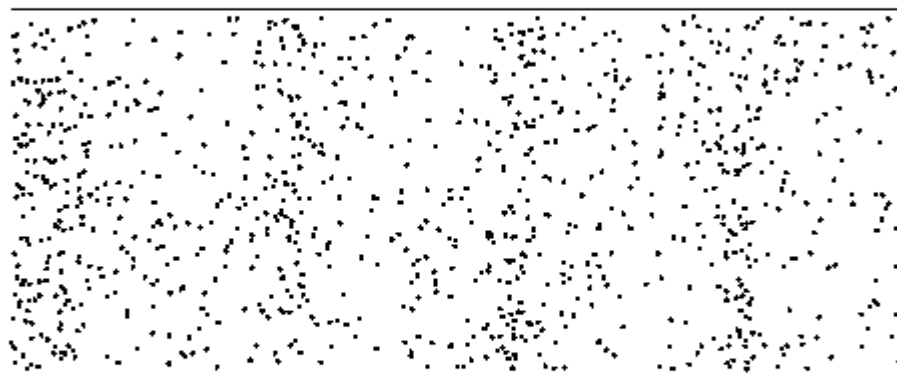
Risuonatore sferico

$V = 0.00292 \text{ m}^3$ ,  $L = 0.08 \text{ m}$  (cilindrico),  $S = 0.00083 \text{ m}^2$  (circolare)

$L_{\text{eff}} = 0.105 \text{ m}$ ,  $f = 90 \text{ Hz}$

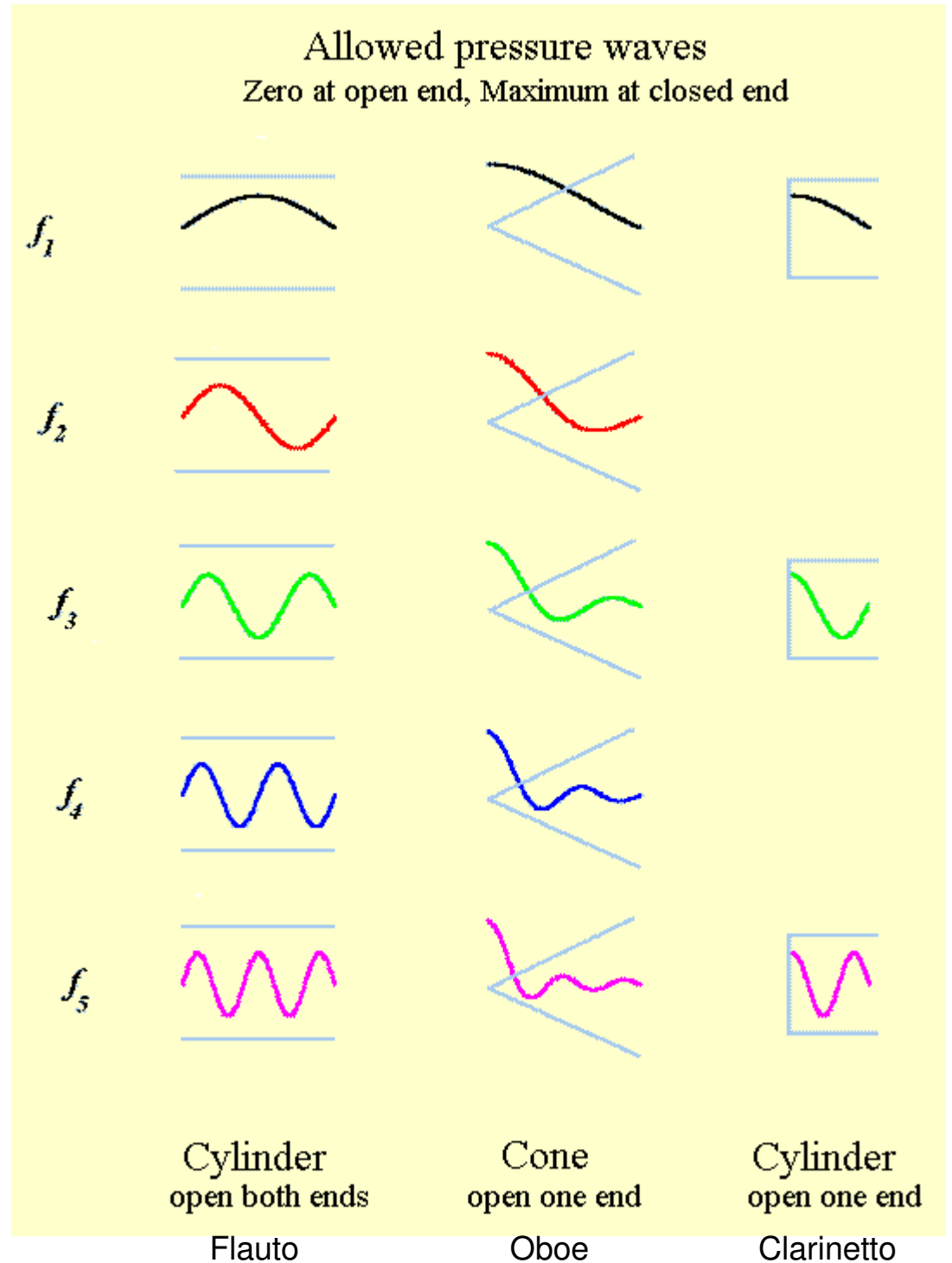
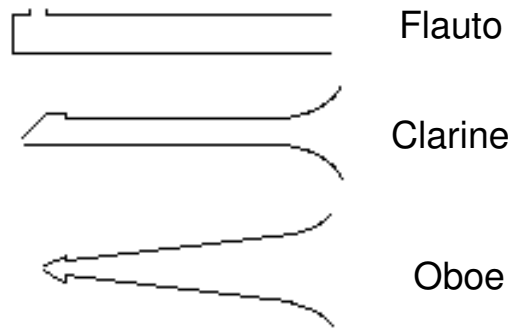


# ONDE STAZIONARIE IN CANNE

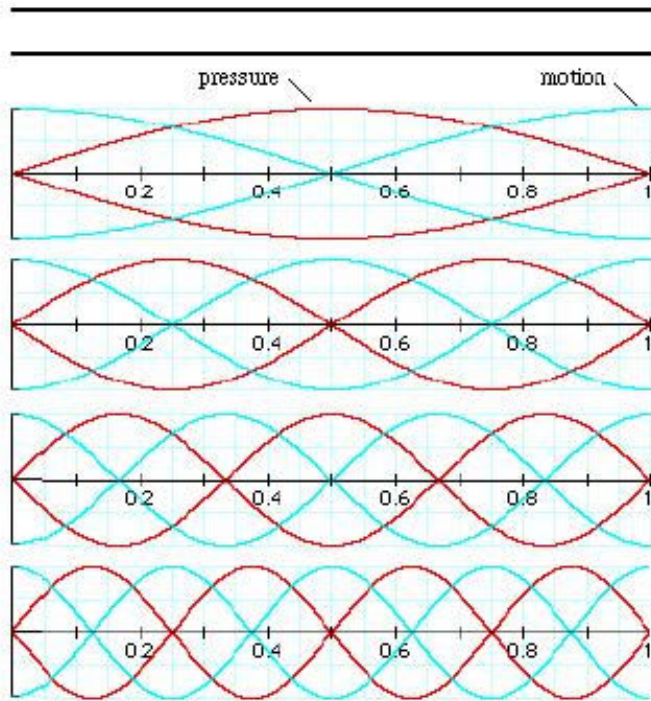


Nodi di pressione e di spostamento

# FORME DI CANNE

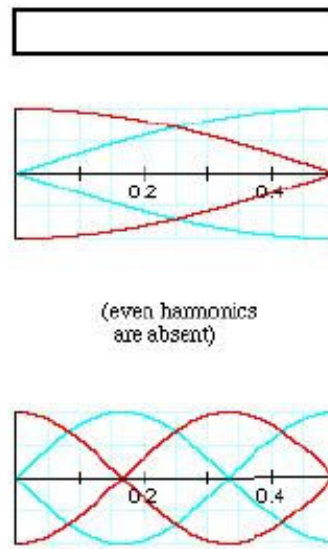


# FORME DI CANNE



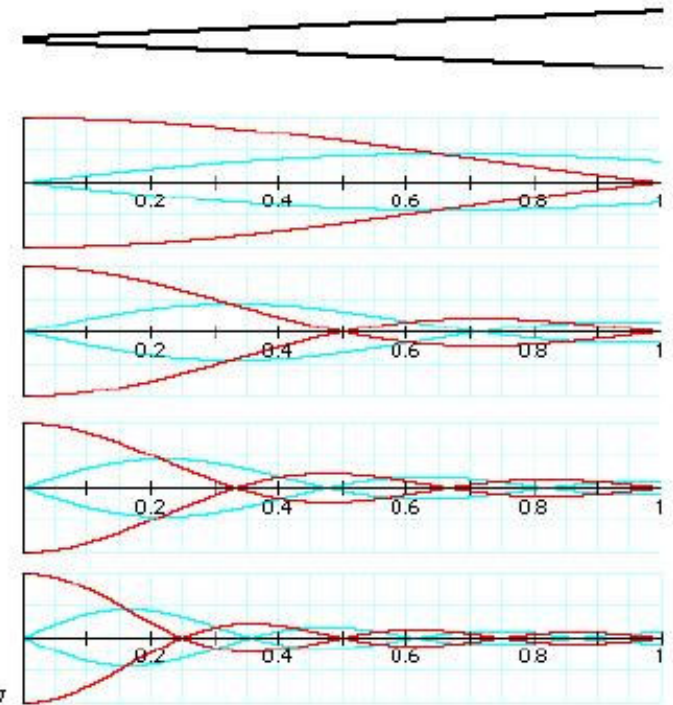
Canna aperta da due lati  
 $\lambda=2L/n$

**Flauto**



Canna aperta  
 da un lato  
 $\lambda=4L/n$

**Clarinetto**



Canna conica  
 $\lambda=2L/n$

**Oboe**

Fondamentale  $\frac{1}{2}$  a parità di lunghezza

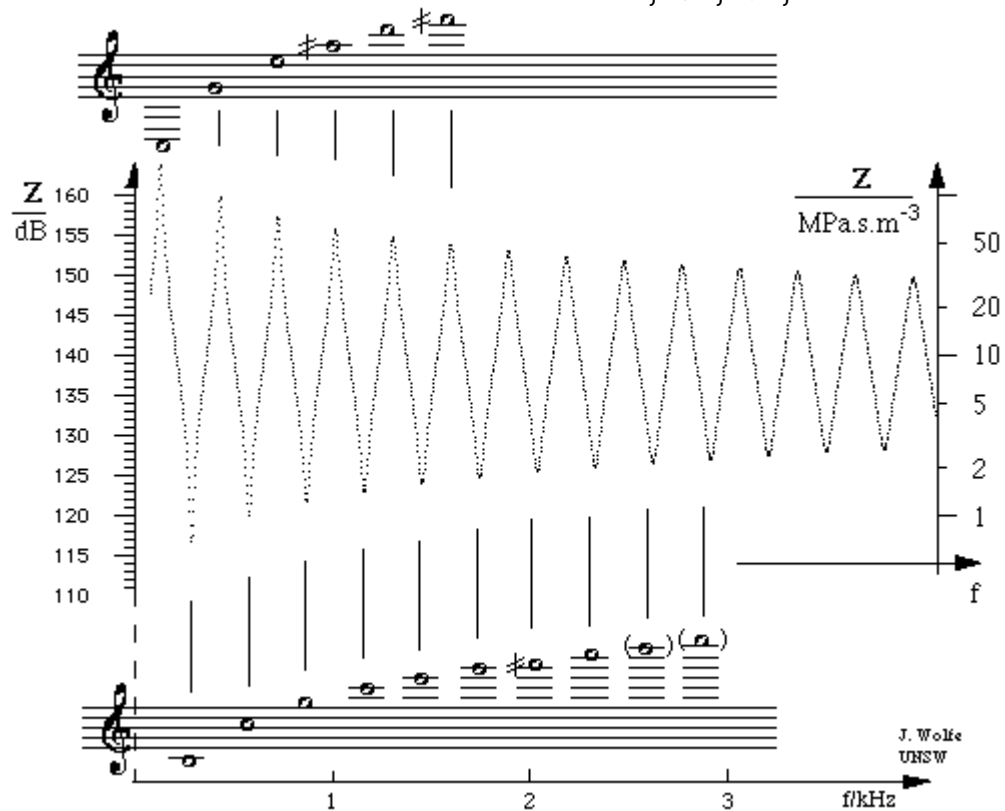
# FORME DI CANNE

Armonica successiva 12 note piu' in alto,  
non possibile eseguire tutta la scala con tasti



Clarinetto: massimi di  $Z$   
 $f, 3f, 5f, \dots$

Impedenza acustica  
di un tubo cilindrico



Flauto: minimi di  $Z$   
 $f, 2f, 3f, 4f, \dots$

# FORME DI CANNE

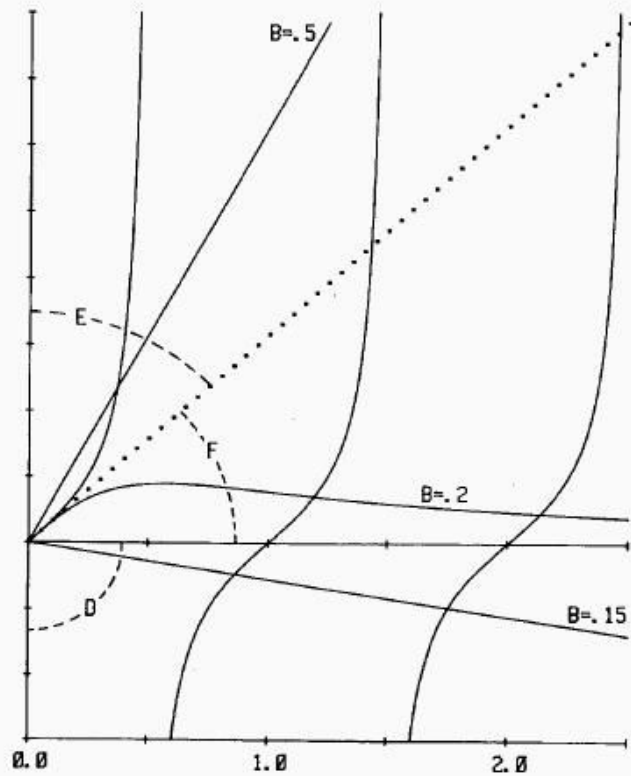
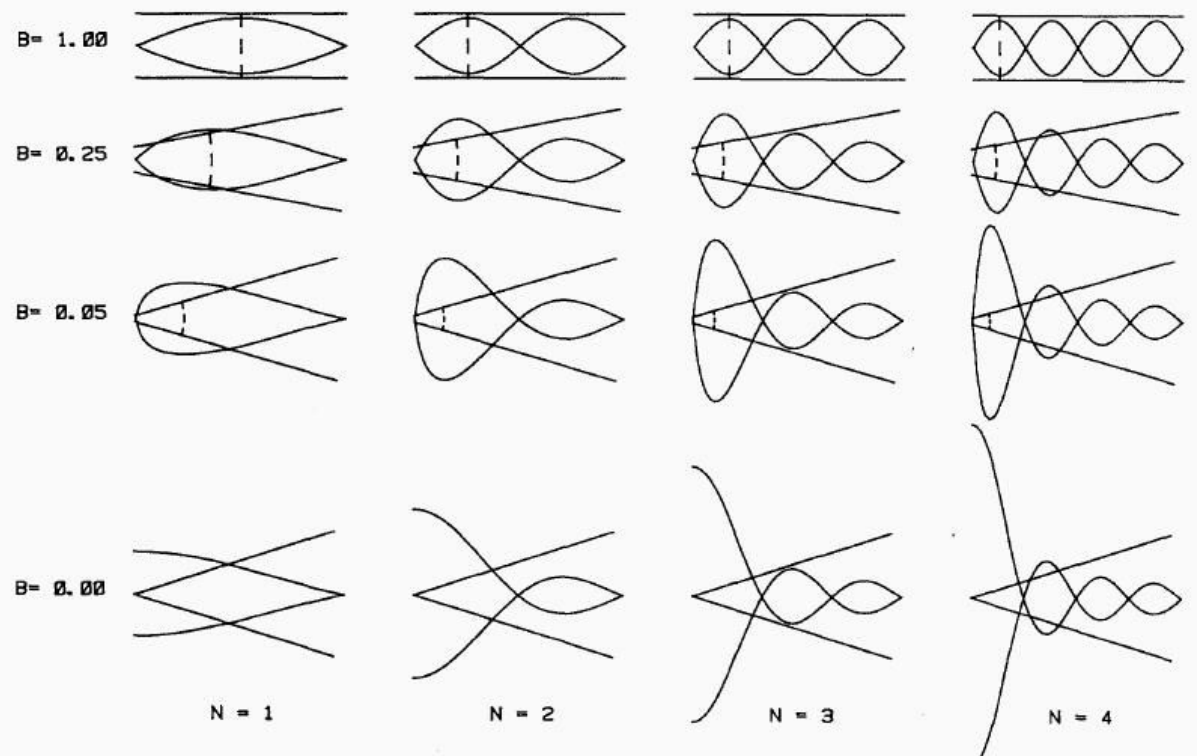
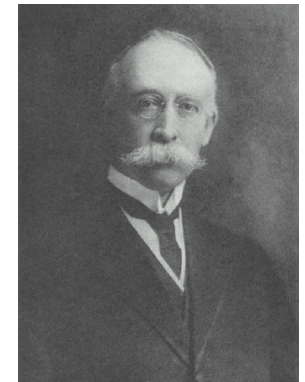
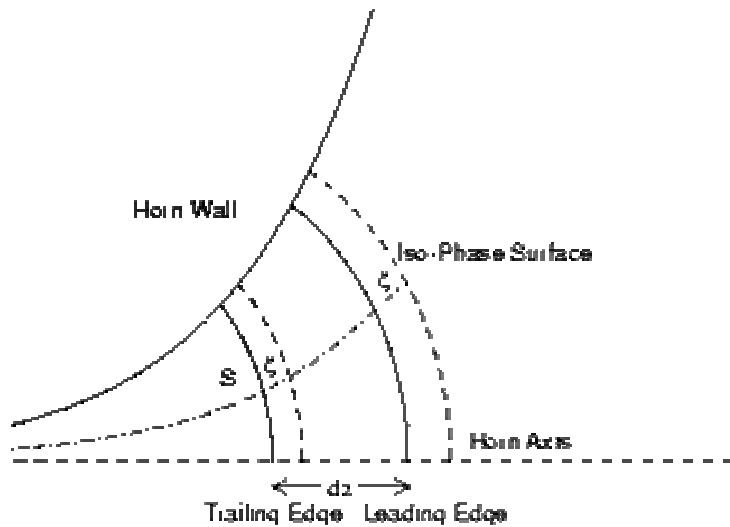


Fig. 2. Graphical solutions of the transcendental equations for the modal frequencies. Quadrant *D*, closed–open frustum; octant *E*, open–closed frustum; octant *F*, closed–closed frustum.





# EQUAZIONE DEL CORNO



**Arthur Gordon Webster**  
(1893-1913)

$$\frac{1}{S} \frac{\partial}{\partial z} \left( S \frac{\partial p}{\partial z} \right) = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}$$

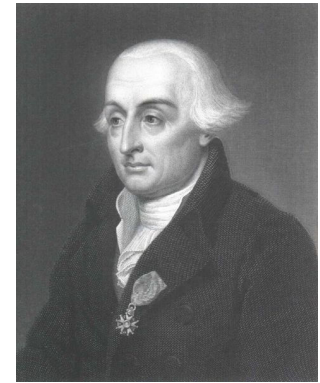
$$c^2 = B / \rho$$



**Leonhard Euler**  
(1707-1783)



**Daniel Bernoulli**  
(1700-1782)



**Joseph-Louis Lagrange**  
(1736-1813)

# STRUMENTI A FIATO

# LEGNI



recorder



bassoon



clarinet



double bassoon



piccolo



oboe

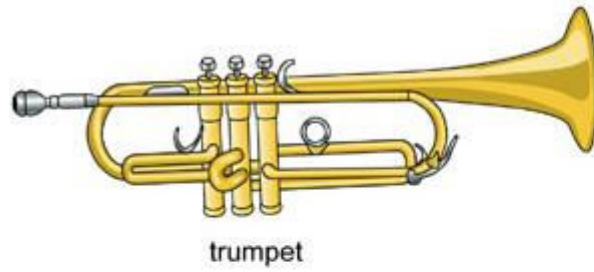


transverse flute



English horn

# OTTONI



# ANCE E BOCCHINI



French horn



trombone



trumpet



transverse flute



recorder



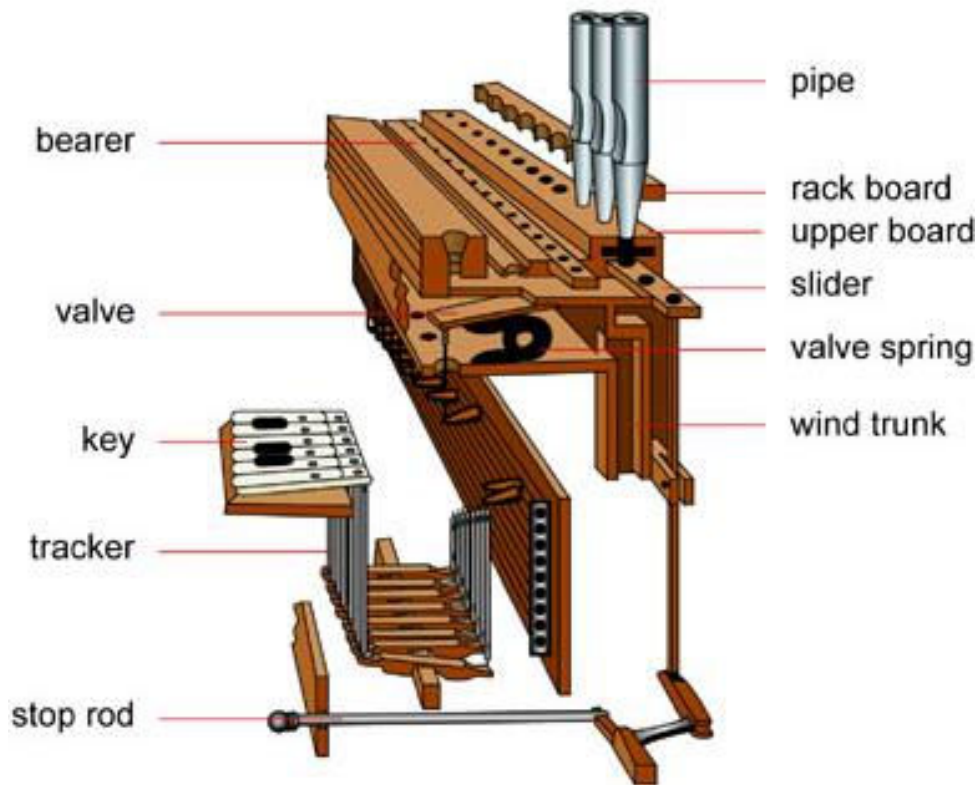
oboe



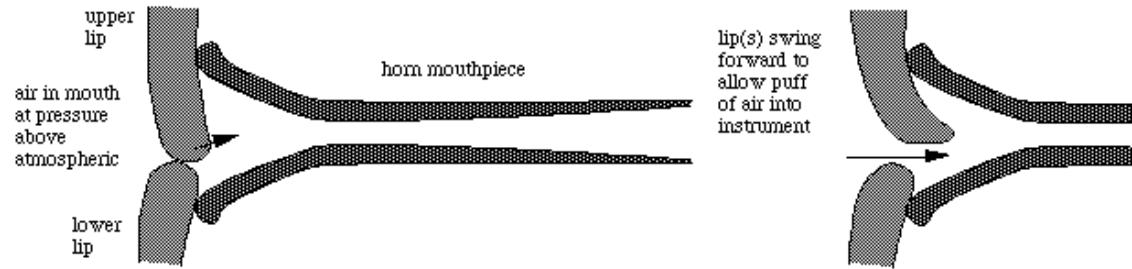
clarinet



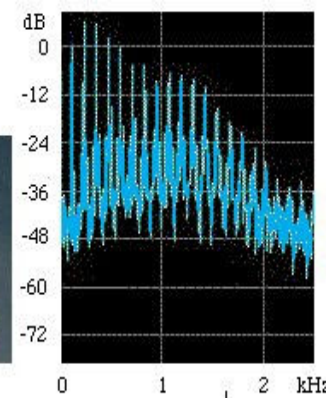
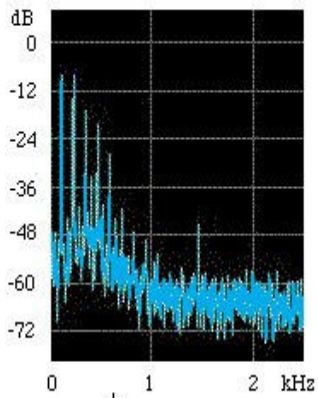
# ORGANO



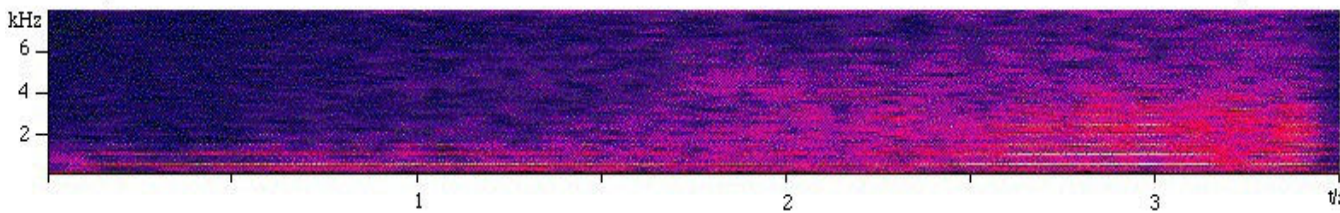
# OTTONI



Moto delle labbra



Contenuto armonico crescente con la forza del soffio (clipping)



# OTTONI



Canna semplice



Canna con campana

Armoniche piu' alte e ravvicinate



Tromba completa di  
bocchino

Aggiunta e soppressione risonanze



Tromba senza/con sordina

Attenuazione selettiva (formanti)



# LA VOCE UMANA

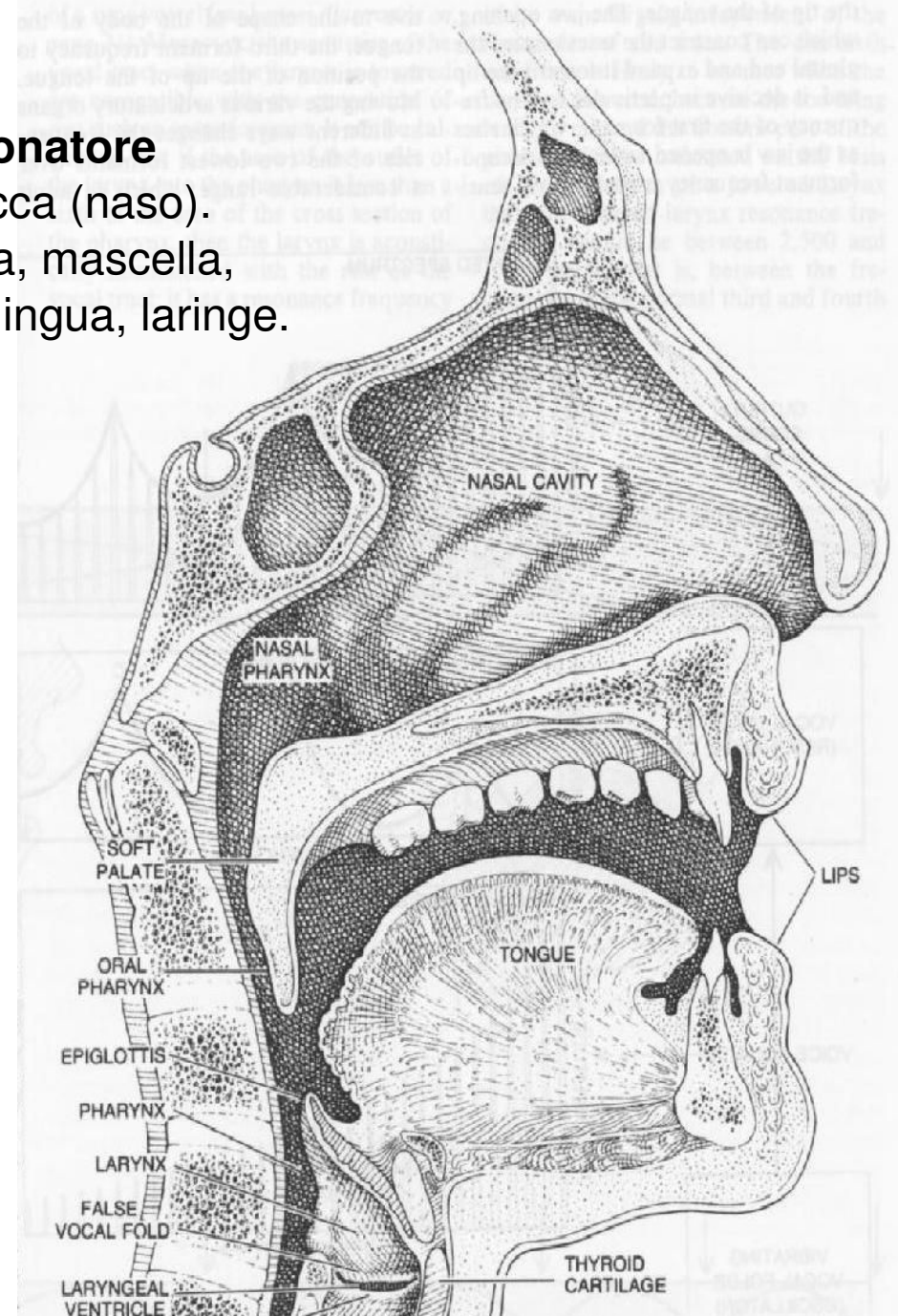
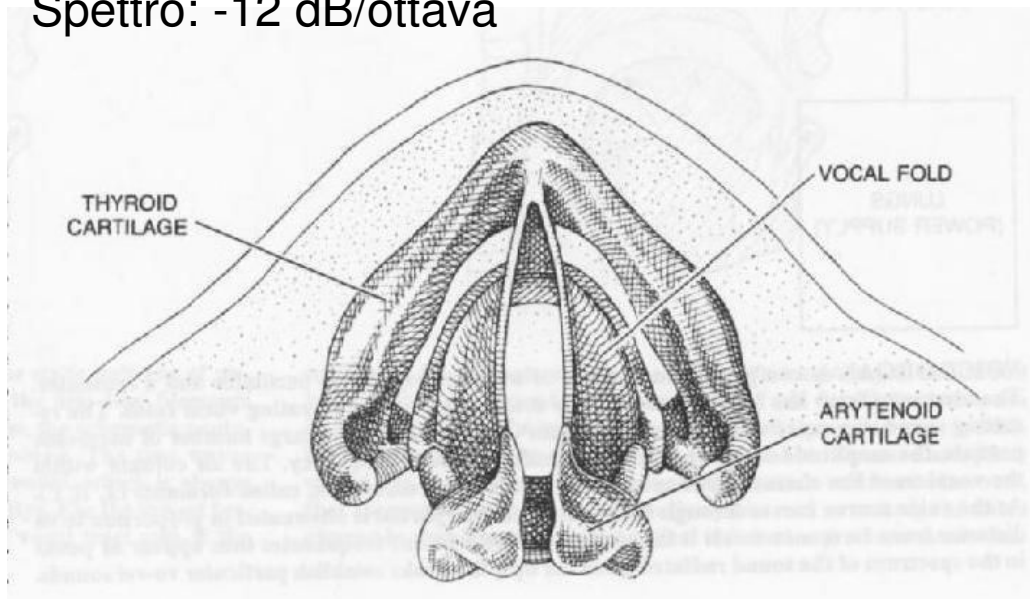
# FISIOLOGIA

## Tratto vocale: risuonatore

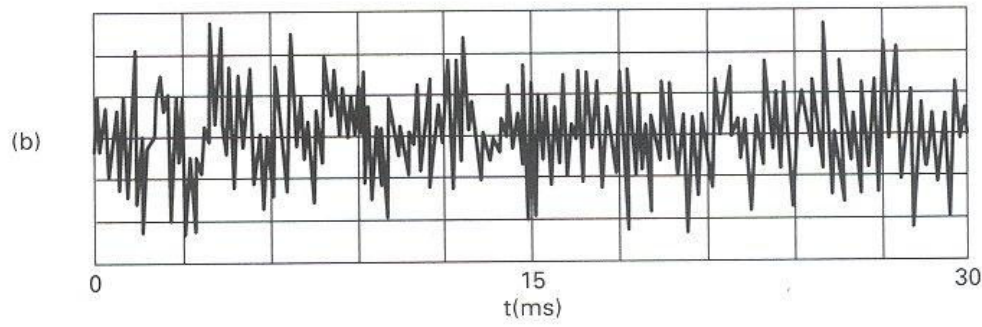
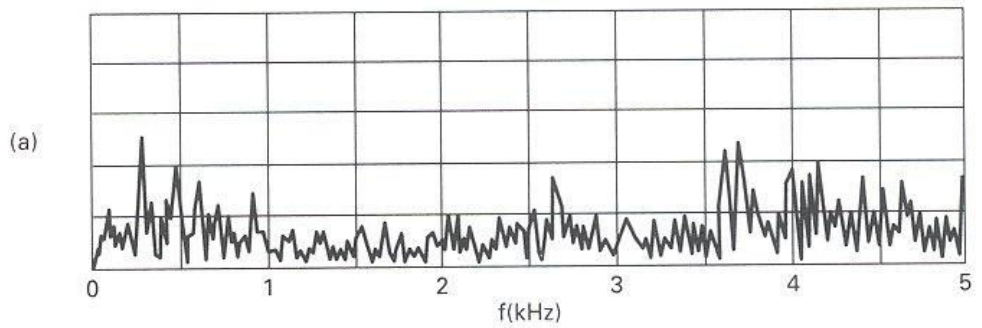
Laringe, faringe, bocca (naso).  
Modificato da: labbra, mascella,  
punta e corpo della lingua, laringe.

## Corde vocali: oscillatore

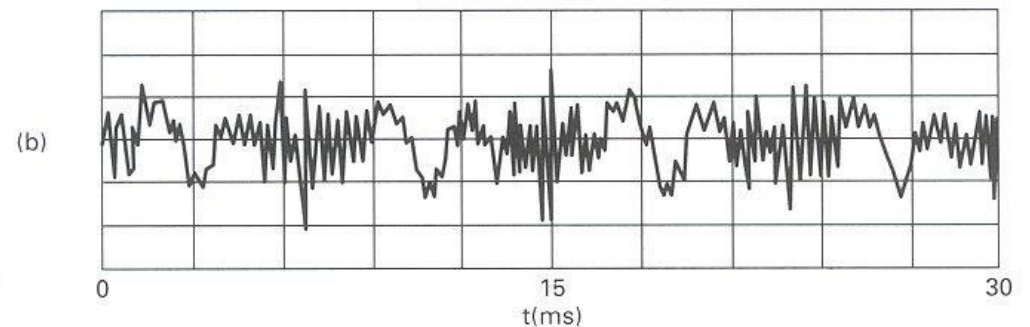
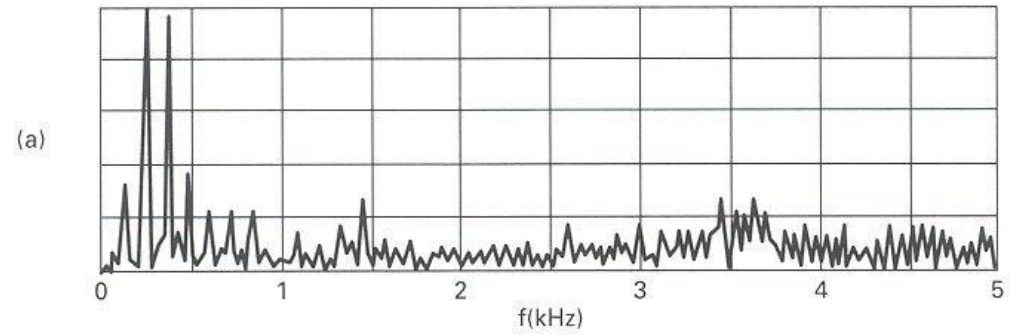
Flusso di aria, effetto Bernoulli  
Frequenza fondamentale crescente  
con la pressione e la tensione  
Spettro: -12 dB/ottava



# SIBILANTI



**SSS**

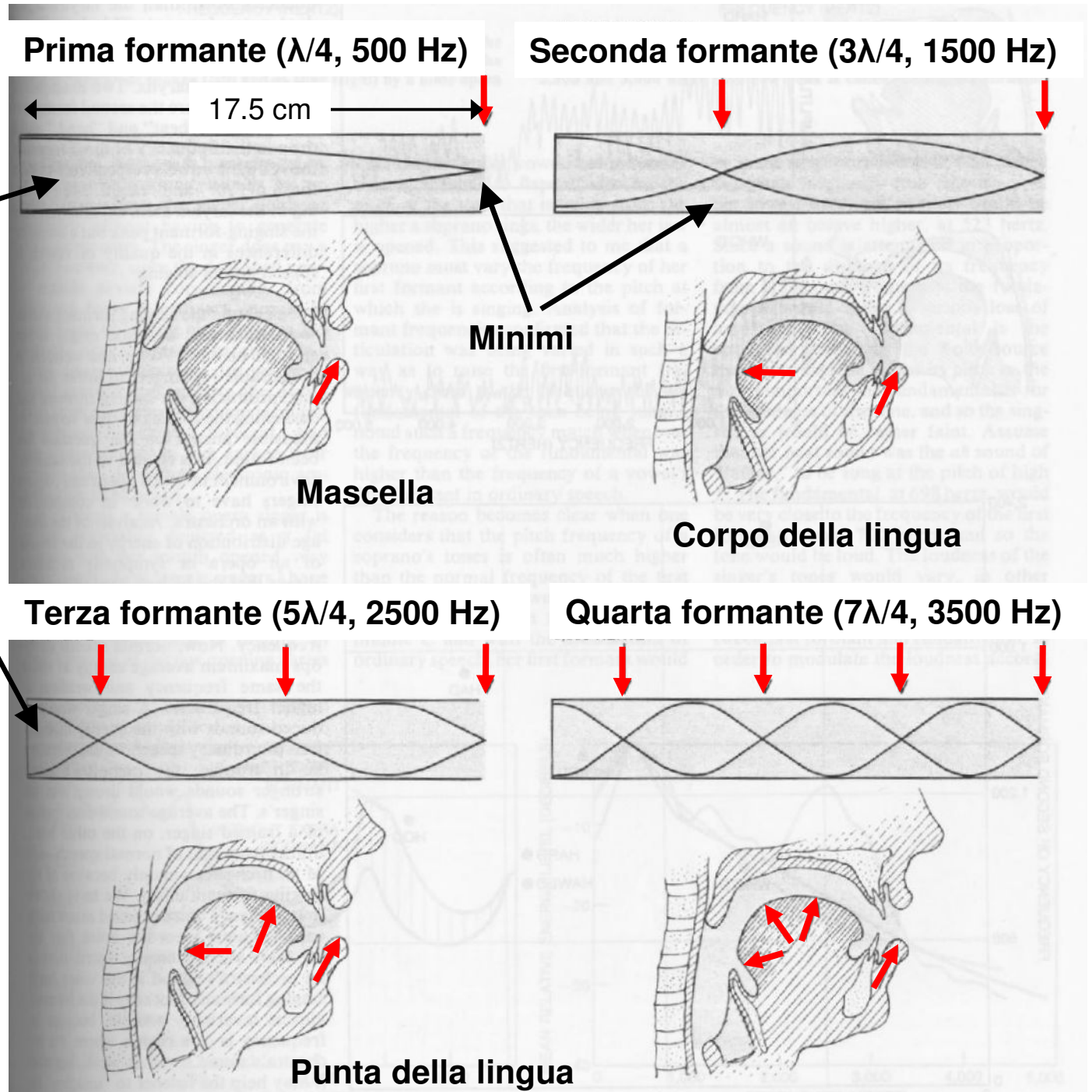


**ZZZ**

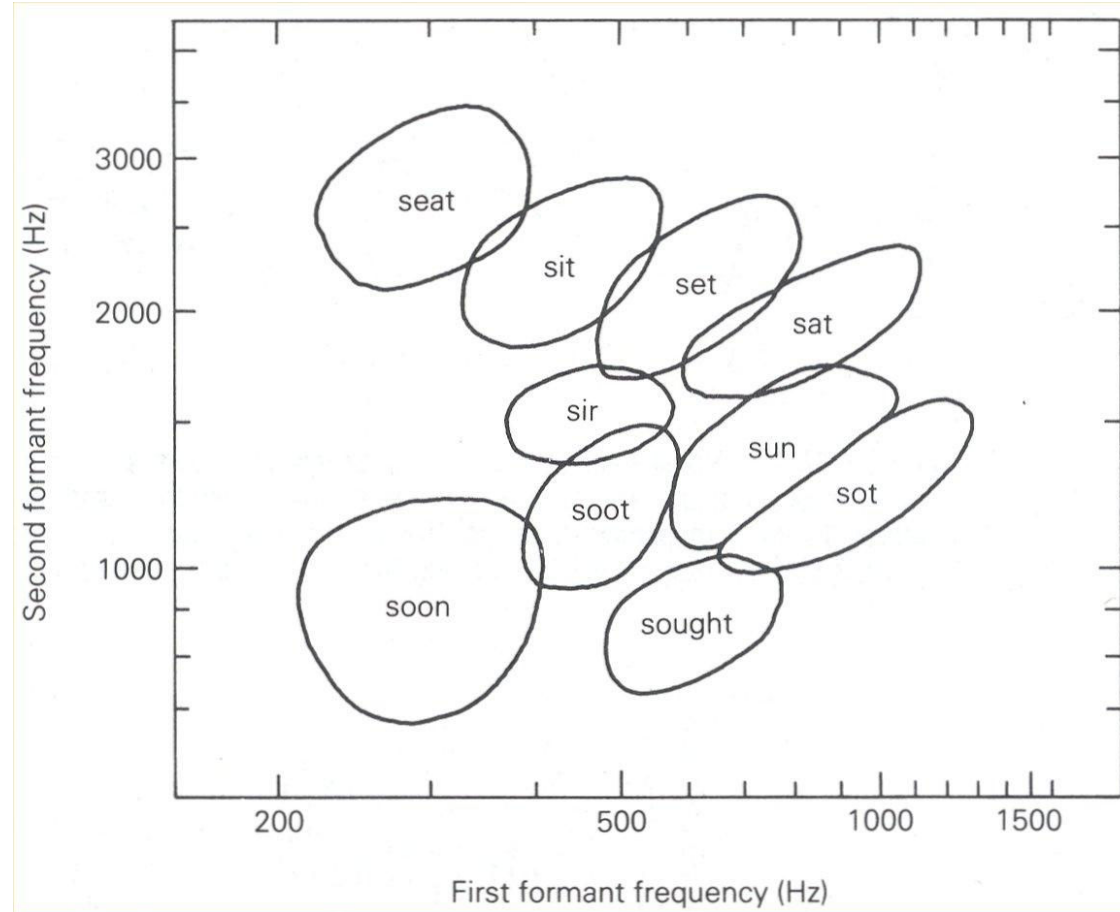
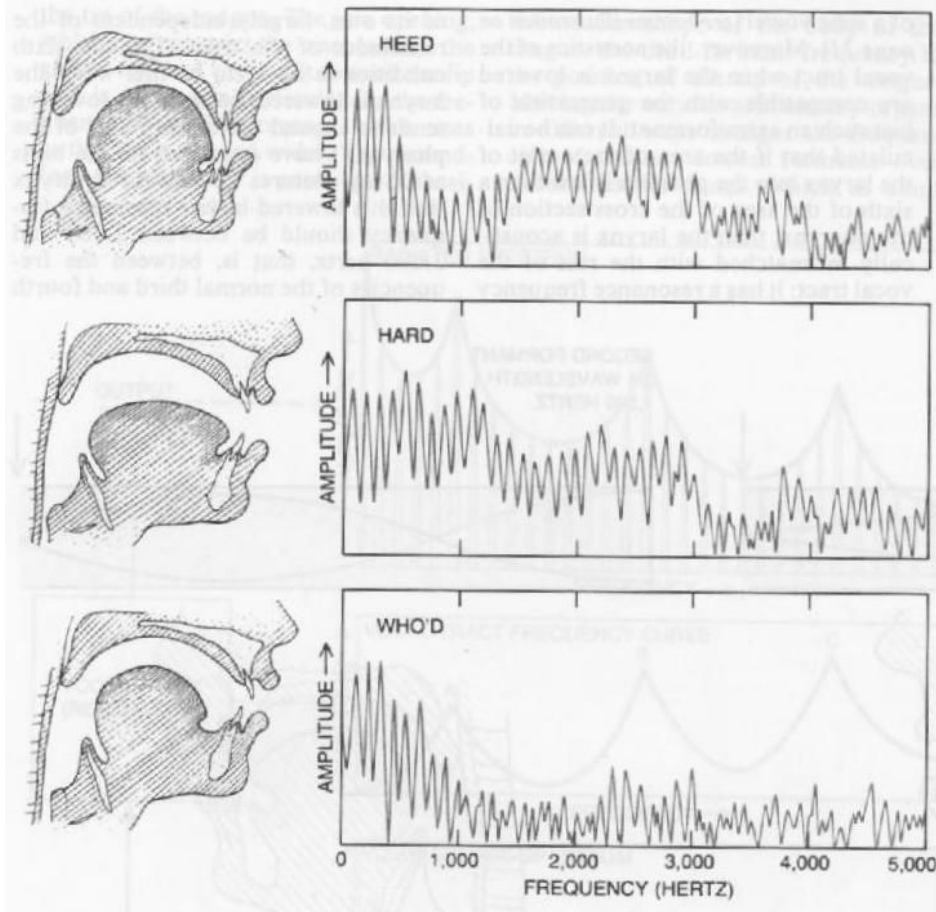
# FORMANTI

Ampiezza di pressione

Riduzione del diametro in un punto di minima pressione = riduzione della frequenza

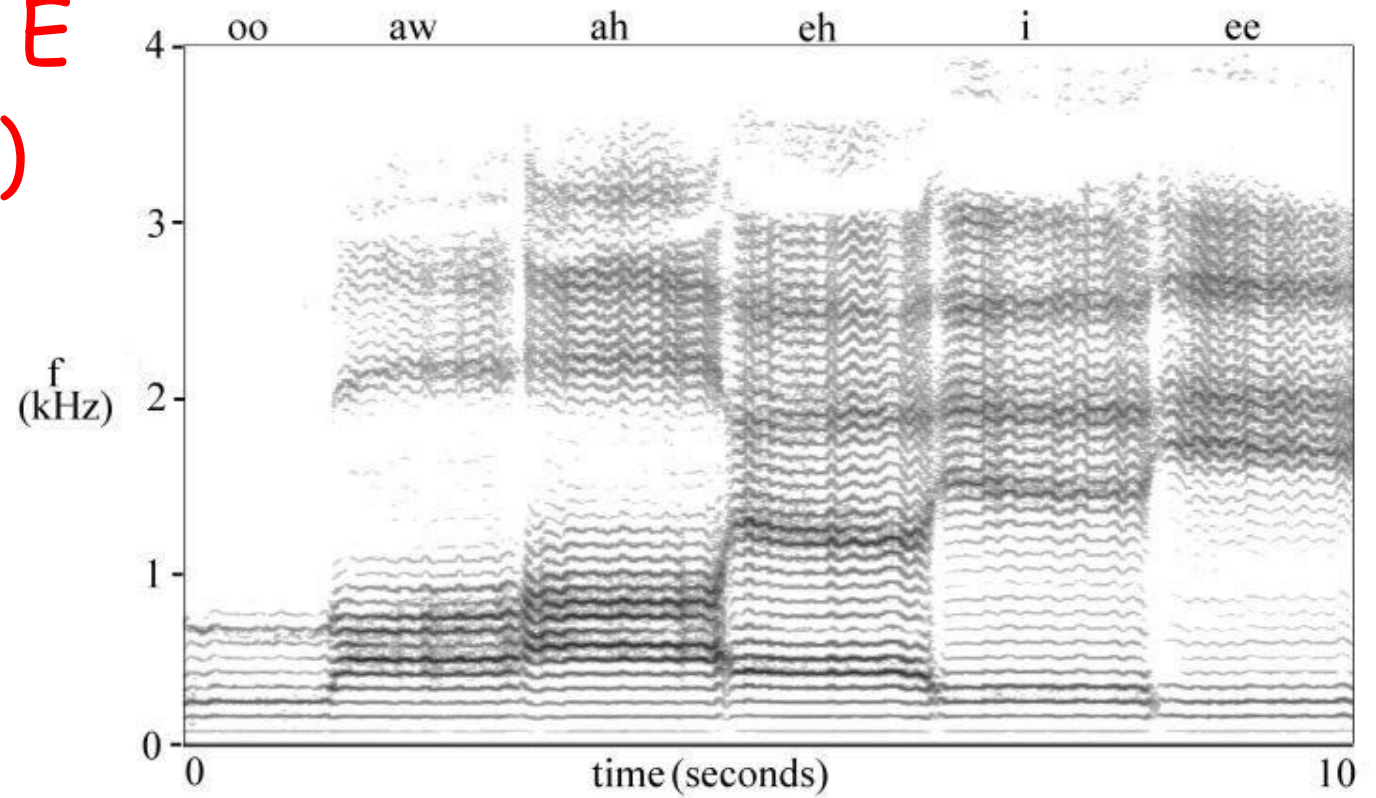


# FORMANTI E VOCALI (1)



Lo spettro varia con la frequenza

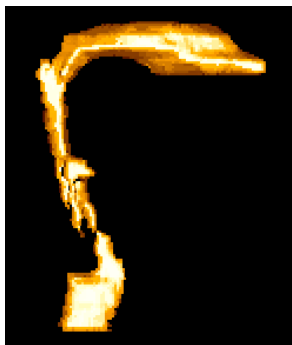
# FORMANTI E VOCALI (2)



Immagini MRI del tratto vocale



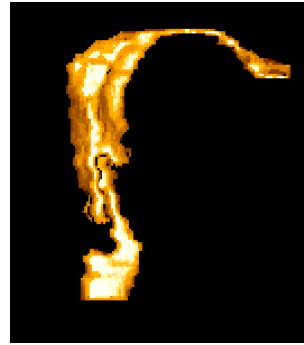
**oo**



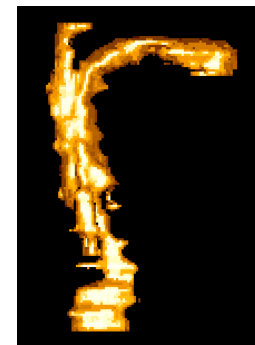
**ah**



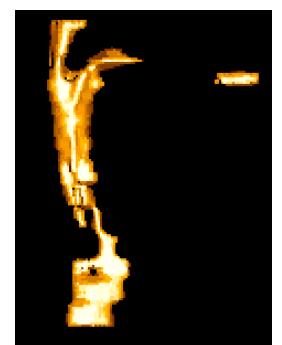
**eh**



**ii**



**mm**



**nn**

# VOCE

Intervallo di frequenze: 200-8000 Hz  
(telefono 300-3000 Hz,  
fondamentale mancante)

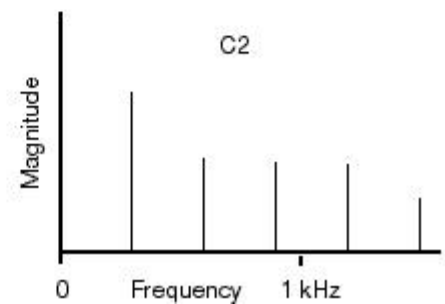
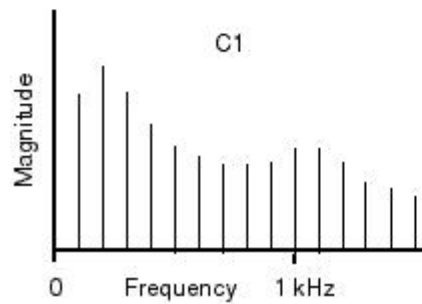
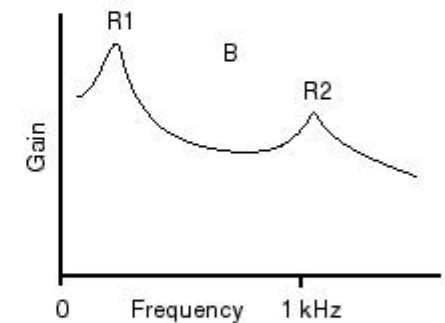
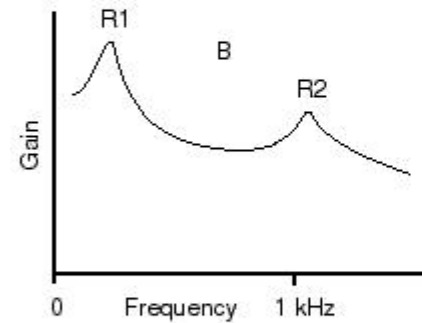
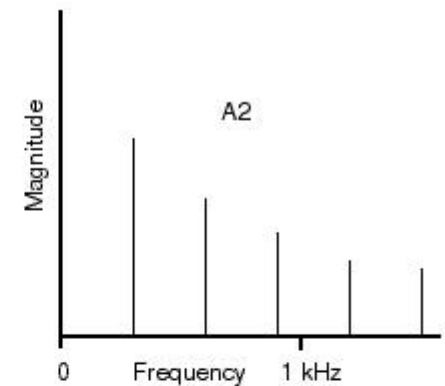
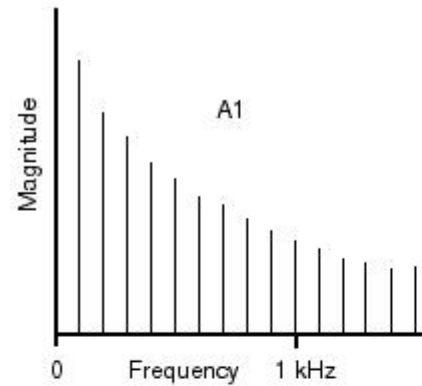
Densita' minore = v maggiore =  
risonanze a frequenze maggiori



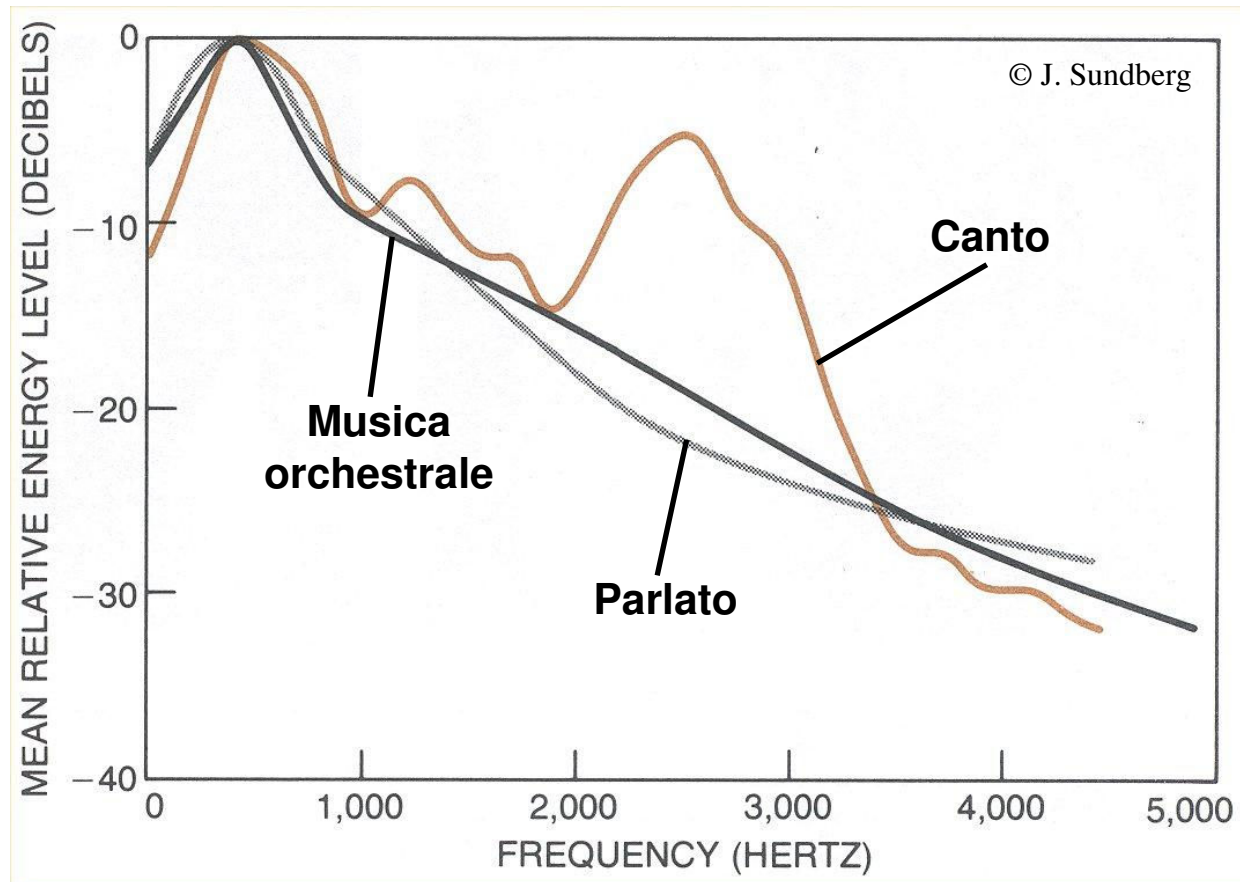
Tono in aria



Tono in elio



# FORMANTI E CANTO

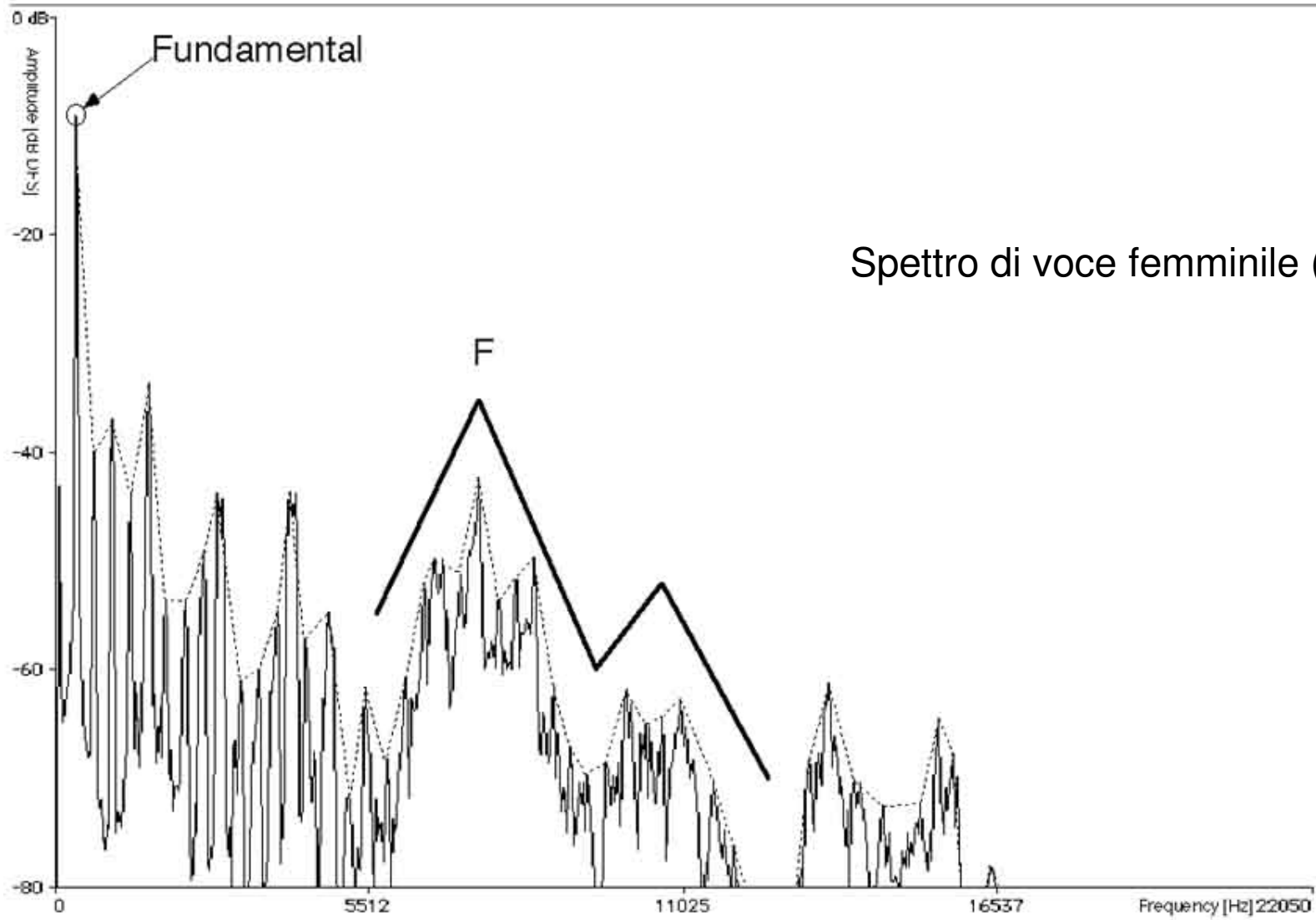


Formante “addizionale” tra la terza e la quarta: abbassamento della laringe (diametro  $< 1/6$  della faringe), risonanza propria. Udibilita' nell'orchestra.

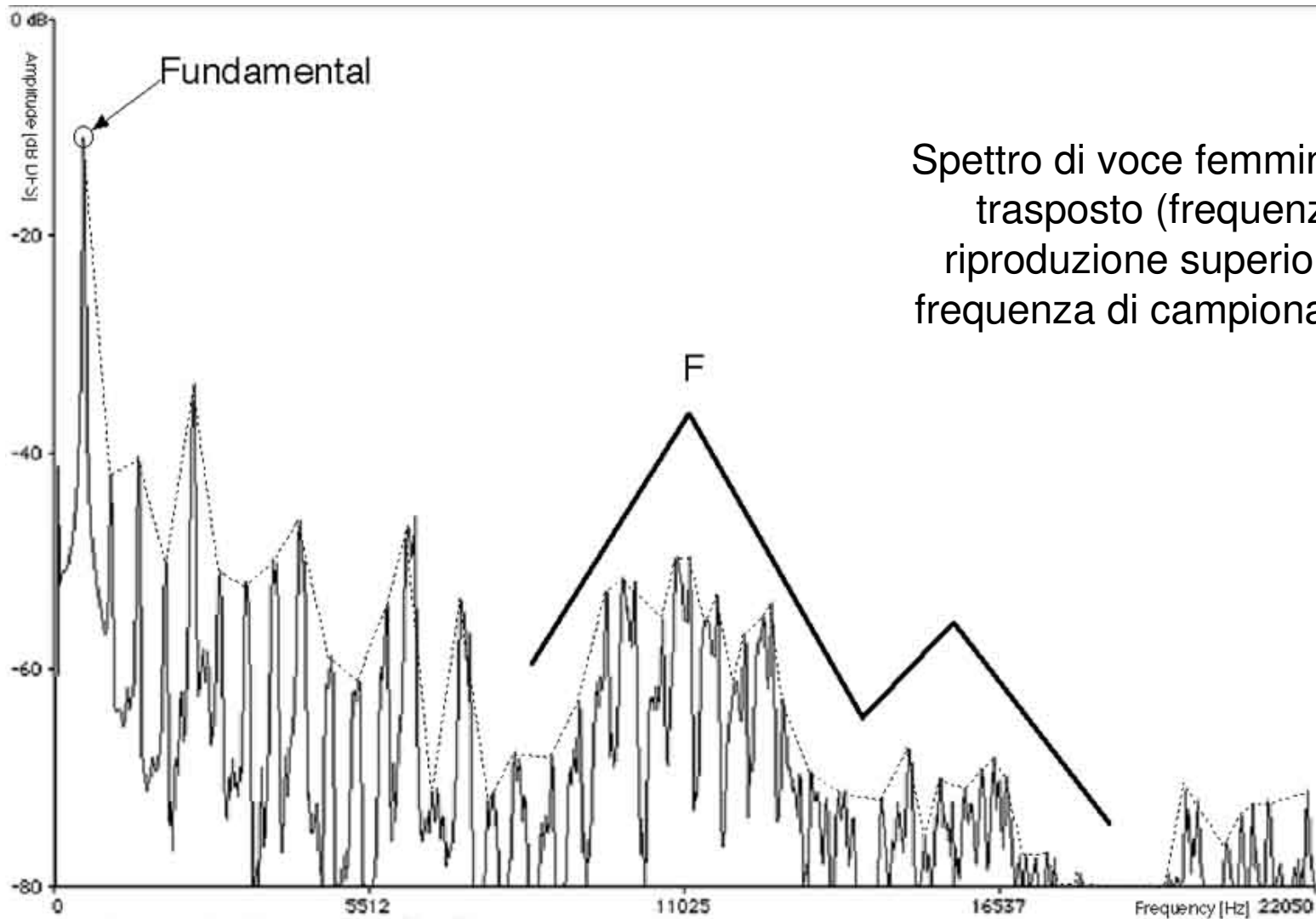
Spostamento della prima formante per adattarsi all'altezza: riduzione della dinamica per altezze diverse.



# FORMANTI

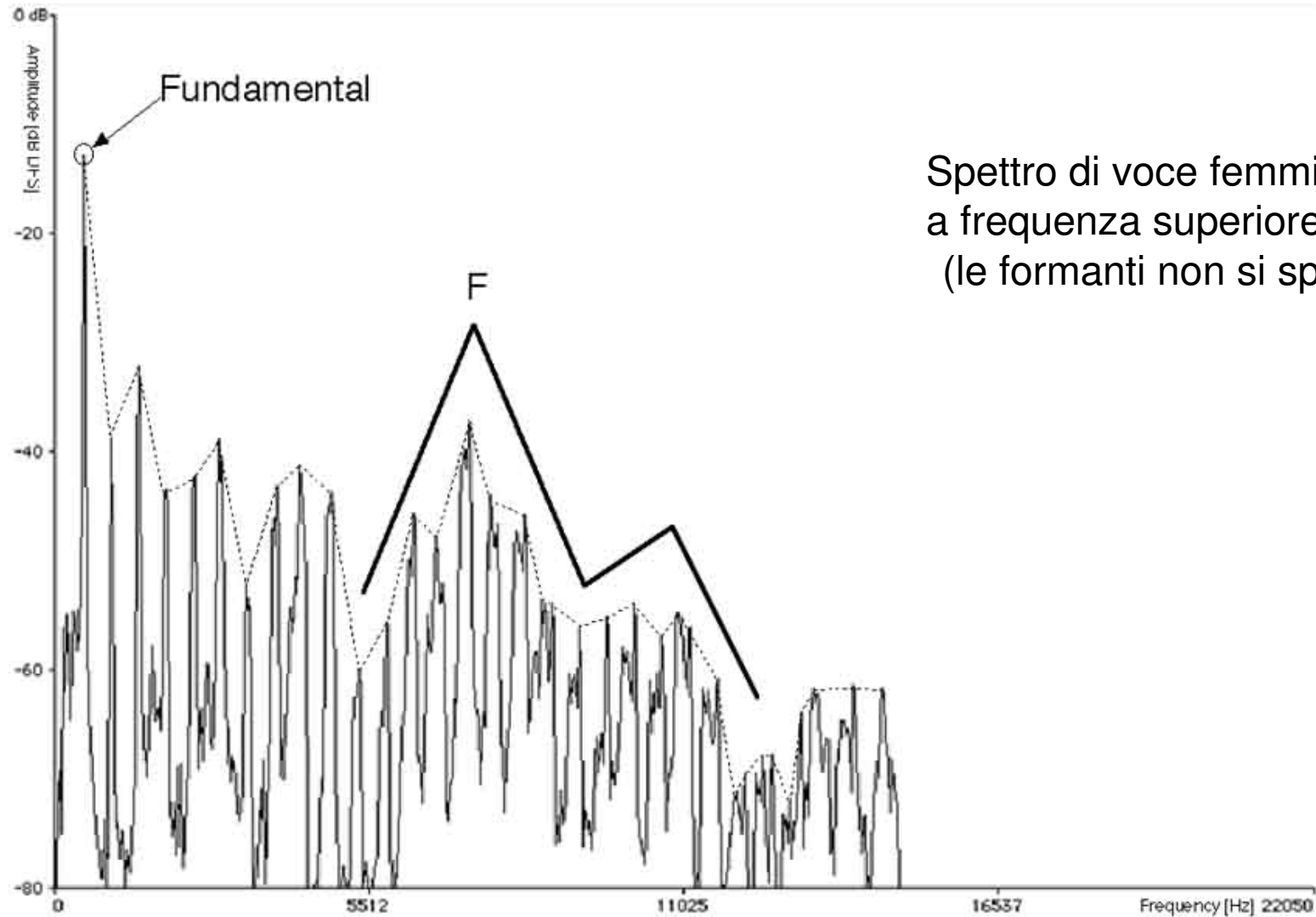


# FORMANTI



Spettro di voce femminile (“a”)  
trasposto (frequenza di  
riproduzione superiore alla  
frequenza di campionamento)

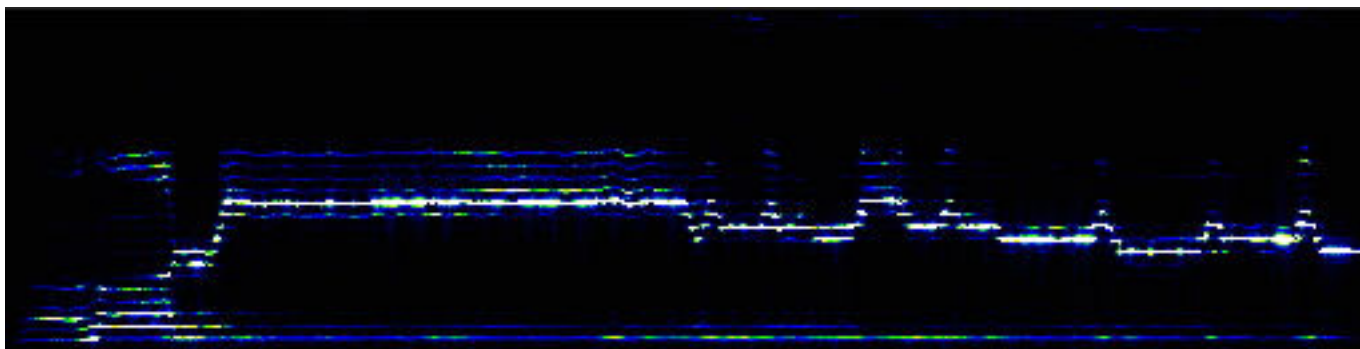
# FORMANTI



Spettro di voce femminile (“a”) a frequenza superiore corretto (le formanti non si spostano)

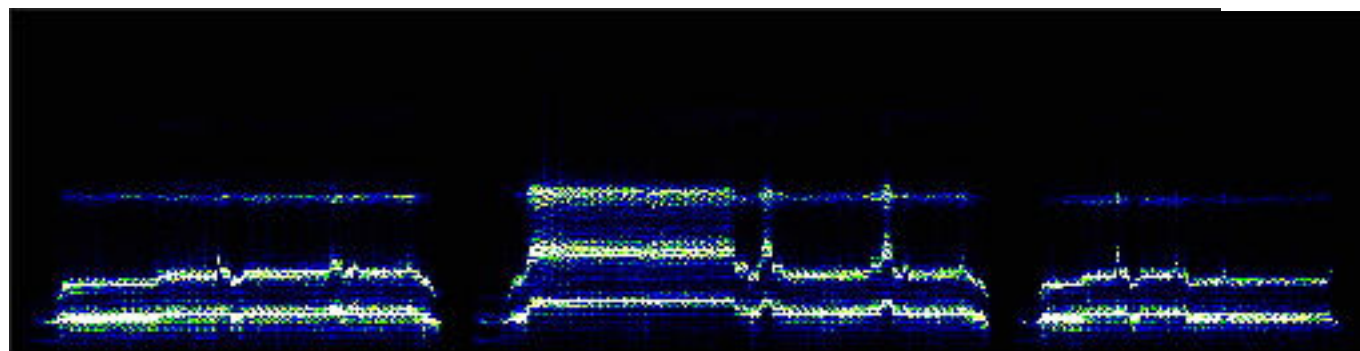
# CANTO AD OVERTONI (KHOOMEI)

Repubblica di Tuva (Tyva)  
pop. 300000  
Indipendente dal 1921  
Parte dell'URSS dal 1944  
Ora nella CSI



**Sygyt**

5300 Hz

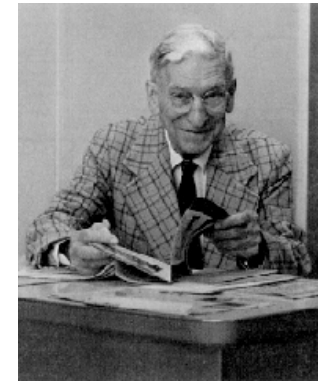


**Kargyraa**

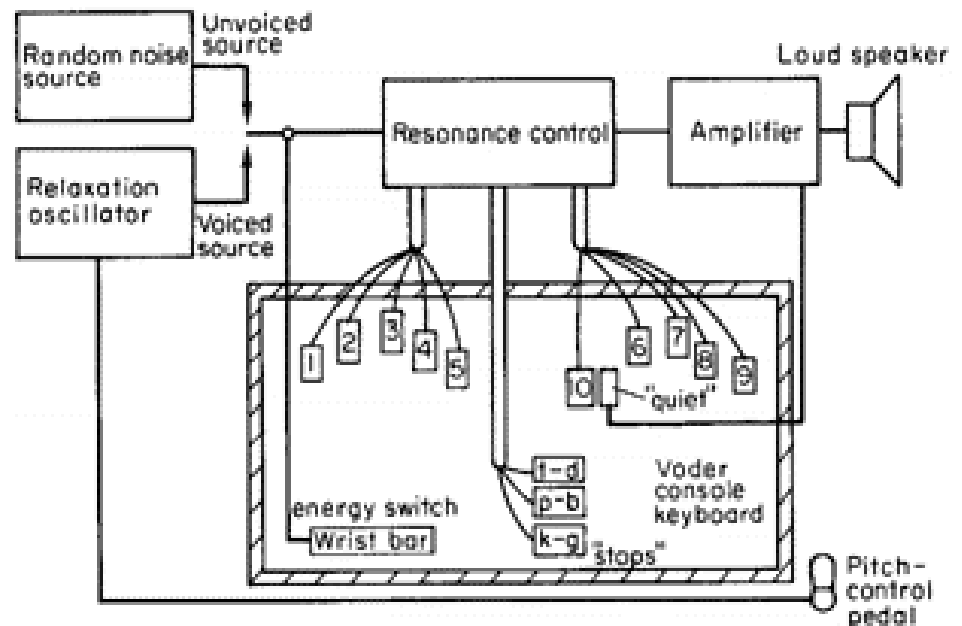
5470 Hz

# IL VODER

Homer Dudley (1939)  
Voice Operating Demonstrator  
Oscillatore a frequenza variabile  
Sorgente di rumore  
10 filtri risonanti passa-banda



Homer Dudley  
(1896-1980)



# IL VOCODER (1)

H. Dudley (1928) - Voice Coder

Per trasmissione della voce su linee telefoniche  
(300 Hz anziché 3000 Hz – oggi 8 kb/s)

VODER preceduto da uno stadio analizzatore  
con secondo banco di filtri ed *envelope followers*  
che controllano il guadagno dei filtri di sintesi

8-32 bande di analisi e sintesi

Frequenze sopra 8 kHz trasferite all'uscita per fornire  
energia per le sibilanti e fricative



Trasparente



Accordi

Vocoder anni '70



KORG VC10



KORG MS2000B



# IL VOCODER (2)

